CLAY MINERALS AND HYDROXY INTERLAYERS IN SELECTED OKLAHOMA SOILS

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CHAPTER I

INTRODUCTION

The study of soil clay minerals is essential to more fully understand soil physical and chemical properties such as shrink-swell potential, cation exchange capacity, K reserve and release rates, K and NH_4 fixation potential, phosphate fixation, etc. Determination of clay minerals is also needed to properly place soils with more than 35% clay content into the correct family classes according to Soil Taxonomy. Methods used extensively for identification of clay minerals are X-ray diffraction analysis, differential thermal analysis, the electron microscopic technique, infra-red analysis, specific surface area, and cation exchange capacity. Total K content of clay has been used to estimate the amount of illite. Selective dissolution analysis has been used to determine the amounts of amorphous clay or allophane and of kaolinite plus halloysite. Montmorillonite and vermiculite can be determined quantitatively based on cation exchange or specific surface area analyses.

Expansible 2:1 clay minerals in soils are usually interlayered due to a high degree of weathering. Interlayer materials influence cation exchange capacity, shrink-swell potential, ion fixation and selectivity, and transformation of clay minerals. Several methods have been used to remove and measure the amounts of interlayers. Most of those methods are based on the ability of fluoride and citrate ions to form

complexes with Al and Fe. However, new methods based on the selective destruction of hydroxy groups upon heating at different temperatures have been developed.

Presence of interlayers and poor crystalline clay minerals in most Oklahoma soils creates difficulties in identifying clay minerals using X-ray diffraction. Therefore, determination of the extent of interlayer materials and alkali-soluble amorphous clays is essential for a better understanding of the clay mineral composition of these soils. Quantitative determination of amorphous clays, kaolinite, illite, vermiculite, and montmorillonite were obtained using selective dissolution analysis, total K_2O content, and cation exchange analysis. The soils studied represented five geologic periods in Oklahoma, i.e., Permian, Pennsylvanian, Cretaceous, Tertiary, and Quaternary. Permian deposits are the most extensively present in the state. The selected soils were also formed under widely differing climatic conditions ranging from a semi-arid climate with a mean annual precipitation of 48 cm to a humid climate with a mean annual precipitation of 119 cm. Although a number of investigators have studied soil clay minerals in specific soils in the state, there is a need to know the overall distribution pattern of those minerals over the state. Therefore, by using the contributions of other workers combined with the author's present research, a generalized map showing clay mineral distribution has been prepared for the state. Clay minerals of 49 soils are reported and related to the origin of their parent materials.

The research reported in this dissertation has been divided into three chapters. The first two chapters are manuscripts prepared for publication and will be submitted to scientific journals with only minor

modifications. The other chapter is prepared in a format to be published as a research bulletin.

CHAPTER II

OCCURRENCE OF HYDROXY INTERLAYERS AND ALKALI-SOLUBLE AMORPHOUS CLAYS IN SELECTED OKLAHOMA SOILS

Amorphous clays and interlayer materials influence the physical and chemical properties of soil clays significantly. The main objective of this study was to investigate the extent of hydroxy-Al and -Fe interlayers and of alkali-soluble amorphous clays in six Oklahoma soils developed in materials of five geologic ages under a range of climatic conditions.

Pearson and Ensminger (1949) found a 14 Å mineral with properties different from those of montmorillonite, vermiculite, or chlorite in Alabama soils. MacEwan (1950) concluded that oxides of iron and aluminum were distributed irregularly between the mica layers and prevented the clay minerals from collapsing completely when water was expelled upon heating to 540°C. Brown (1953) showed evidence of "blocking material" in the interlayer space. He extracted the material with KOH-HCl and suggested that aluminum was the principal component. Since that time, the occurrence of interlayering materials in soil clays has been studied and reported by many investigators (Dixon and Jackson, 1960; Dixon and Seay, 1957; Glenn et al., 1960; Jackson et al., 1954; Klages and White, 1957; Quigley and Martin, 1963; Rich and Obenshain, 1955; Tamura, 1956; Whittig, 1959).

Although interlayers are usually found to be composed largely of Al, there are some reports that Fe could precipitate with Al (Jackson, 1960; Singleton and Harward, 1971; Weed and Nelson, 1962). Quigley and Martin (1963) presented evidence supporting the presence of a nearly pure hydroxy-Fe interlayer in a soil clay. Rich (1968) suggested moderately acid pH, active weathering, low organic matter content, and frequent wetting and drying cycles were favorable conditions for interlayer formation. Interlayer materials affect cation exchange capacity (Dion, 1944; Paver and Marshall, 1934; Rich, 1968), ion fixation and selectivity (Rich, 1960a and 1960b; Richard and Black, 1964), shrink-swell characteristics (Tamura, 1957) and transformation (Jackson, 1963; Glenn et al., 1960) of clay minerals.

Many different techniques have been developed to determine the nature of interlayering materials. Chemical methods used for removing interlayers are based on the complexing ability of citrate or fluoride for aluminum and iron. However, methods based on the selective destruction of hydroxy groups upon heating at different temperatures have also been proposed. Brown (1953) first used a mixture of KOH and KCl. Rich and Obenshain (1955) employed 1N NH_4F. Sodium citrate was used by Tamura (1958) as a less destructive reagent. Dixon and Jackson (1959, 1962) compared different methods and concluded that heating the sample to 400°C and then boiling in 0.5N NaOH for 2.5 minutes removed larger amounts of interlayer materials.

Commonly used methods for characterizing amorphous materials are based on the high reactivity (thus dissolution) of these materials with various alkali solutions. Historically, both NaOH and Na_2CO_3 solutions have been employed for dissolving amorphous aluminosilicates. Boiling

clays in a dilute Na_2CO_3 solution is commonly used to facilitate complete dispersion of clay particles by dissolution of amorphous cementing materials of aluminosilicates and/or alumina and silica (Jackson et al., 1950; Jackson, 1975). However, dissolution of the more resistant amorphous aluminosilicates by this method is usually incomplete. A boiling solution of 0.5N NaOH was used for the dissolution of amorphous silica from soils (Hardy and Follett-Smith, 1931). This solution was also used for a 4-hour digestion at 100°C to dissolve free silica and/or alumina in samples of montmorillonites and soils (Dyal, 1953; Foster, 1953; Whittig et al., 1957). Rapid dissolution of crystalline layer silicates, such as kaolinite and montmorillonite, in a dilute suspension of boiling 0.5N NaOH has been demonstrated by Hashimoto and Jackson (1960). However, boiling a soil or clay sample for only 2.5 minutes dissolves a large percentage of the free amorphous aluminosilicates and/or silica and alumina without significant effect on the crystalline clays.

Materials

Dennis silt loam, a member of the fine, mixed, thermic family of Aquic Paleudoll, developed under tall grasses in a reworked shale of Pennsylvanian age. This Pedon was sampled in Rogers County which has a humid climate and a mean annual precipitation of 102 cm. It is a moderately well drained soil and has slow permeability.

Bernow fine sandy loam, a member of the fine-loamy, siliceous, thermic family of Typic Paleudult, developed under trees and grasses in a weakly cemented sandstone of Cretaceous age. This Pedon was sampled in Pushmataha County which has a humid climate and a mean annual precipitation of 119 cm. The soil is well drained and moderately

permeable. Bernow soils are typically Alfisols; however, this Pedon, which was sampled in a gradational boundary between Alfisols and Ultisols in eastern Oklahoma, has been classified as an Ultisol.

Aydelotte silty clay loam, a member of the fine, mixed, thermic family of Udertic Paleustalf, developed under native tall and mid-grasses in alternating layers of shale and siltstone of Permian age. This Pedon was sampled in Cleveland County which has a moist subhumid climate and a mean annual precipitation of 84 cm. It is well drained and has very slow permeability.

Konawa fine sandy loam is a member of the coarse-loamy, mixed, thermic family of Ultic Haplustalf. It formed under grasses in a sandy sediment of Quaternary age. This Pedon was sampled in Pottawatomie County which has a moist subhumid climate and a mean annual precipitation of 94 cm. It is well drained and moderately permeable.

Dill very fine sandy loam, a member of the coarse-loamy, mixed, thermic family of Udic Ustochrept, developed under mid- and tall grasses in a weakly cemented, noncalcareous sandstone of Permian age. This Pedon was sampled in Washita County which has a dry subhumid climate and a mean annual precipitation of 68 cm. This soil is well drained and has moderately rapid permeability.

Ulysses clay loam, a member of the fine-loamy, mixed, mesic family of Typic Haplustoll, developed under short grasses in a highly calcareous material of wind laid silt (loess) of Tertiary age. This Pedon was sampled in Texas County which has a semi-arid climate and a mean annual precipitation of 48 cm. It is well drained and moderately permeable.

Table I and Figure 1, respectively, show the morphology and locations of the soils studied.

TABLE I

MORPHOLOGY OF THE OKLAHOMA SOILS SAMPLED

Horizon	Depth	Color	Texture	Structure	Consistence	Boundary	Other Soil Characteristics
	cm	moist					
				Dennis			
A1	0- 28	10YR3/2	sil	2csbk-2mgr	mfr,dsh	cs	Mottling begins in the B1 horizon and persists throughout the solum. Mottles of 10YR4/3, 10YR5/6, 10YR2/1, 10YR5/1, 10YR4/6, 10YR6/1, 10YR5/4, 7.5YR5/4, 5YR5/4, and 5YR4/6 are present. Black stains and coatings of Fe and Mn oxides are present in the B23t horizon and thereafter
A3	28- 38	10YR4/2	sil	2fsbk-2mgr	mfr,dsh	cw	
B21t	38- 53	10YR4/3	sic	2cbk	mfi,dvh	cw	
B22t	53- 84	10YR5/4	sic	2cbk	mfi,dvh	gw	
B23t	84-102	10YR5/6	sic	2mbk	mvfi,dvh	gw	
B31	102-147	10YR5/4	c	2mbk	mvfi,dvh	cw	
B32	147-206	10YR5/6	c	2mbk	mvfi,dvh	cs	
IICr	206-221	-	cl	-	-	-	
				Bernow			
A1	0- 13	10YR5/3	sl	1fgr	mvfr,dsh	cs	
A2	13- 25	10YR6/4	sl	1fgr	mvfr,dsh	as	
B21t	25- 51	10YR6/6	l	1mpr	mfr,dh	gs	
B22t	51- 97	10YR6/6	l	2mpr	mfr,dh	gs	
B23t	97-142	5YR5/8	l	2cpr	mfi,dvh	ds	About 10 percent of the matrix of the B23t and B24t is streaks and pockets (A' 22) of light gray (10YR7/2) sandy loam of the eluvial horizon
B24t	142-203	5YR5/8	l	1cpr	mfi,dvh	-	
				Aydelotte			
A1	0- 13	10YR3/2	sicl	2fsbk-3mgr	mfr,dsh	cs	
B1	13- 23	7.5YR3/2	sicl	2fsbk-3mgr	mfi,dsh	cs	
B21t	23- 53	5YR4/3	sic	2mpr-2mbk	mvfi,dvh	gs	
B22t	53- 69	5YR4/4	sic	1csbk-2csbk	mvfi,dvh	gw	Fine Fe and Mn bodies, nonintersecting slickensides
B23t	69-104	2.5YR4/6	sic	1csbk	mvfi,dvh	gw	Fine and medium Fe and Mn bodies, nonintersecting slickensides, $CaCO_3$ masses at 77 cm
B24t	104-137	2.5 YR4/6	sic	1csbk	mvfi,dvh	gw	Common Fe and Mn bodies, $CaSO_4$ masses
B31ca	137-175	2.5YR4/6	sic	1csbk	mfi,dvh	gw	Black Fe and Mn bodies, $CaCO_3$ masses
B32ca	175-185	2.5YR4/6	sicl	1csbk	mfi,dvh	cw	$CaCO_3$ bodies, few shale and siltstone fragments
Cr	185-239	2.5 YR4/6	sicl	-	-	-	Alternating layers of shale and siltstone
				Konawa			
AP	0- 15	10YR4/2	sl	1fgr	mvfr,dsh	cs	
A2	15- 36	10YR5/3	sl	sg	mvfr,dsh	cs	
B21t	36- 66	5YR4/6	sl	2cpr-1msbk	mfr,dvh	ds	
B22t	66- 97	5YR4/6	sl	1cpr-2msbk	mfr,dh	ds	
B3	97-137	5YR4/6	sl	1cpr	mfr,dh	ds	
C	137-178	5YR4/8	sl	m	mfr,dh	-	
				Ulysses			
AP	0- 15	10YR3/2	cl	1mgr	mfr-dsh	gs	
B1	15- 38	10YR3/2	cl	2msbk	mfr-dsh	gs	
B2	38- 91	10YR3/3	cl	1msbk	mfi-dh	gs	
B3ca	91-122	10YR4/3	cl	1cgr	mfr-dsh	gs	$CaCO_3$ concretions, calcareous
Cca	122-163	10YR4/3	l	m	mfr-dsh	-	$CaCO_3$ bodies, calcareous
				Dill			
A11	0- 10	5YR3/4	vfsl	1fgr	mvfr,dh	cs	
A12	10- 36	5YR3/4	vfsl	1fgr	mvfr,dh	gs	
B21	36- 53	2.5YR3/4	vfsl	1mpr-1fgr	mvfr,dh	gs	
B22	53- 84	2.5YR3/4	vfsl	1mpr-1fgr	mvfr,dh	dw	Few fragments of soft sandstone
IIC	84-119	10YR4/6	vfsl	-	-	-	Red soft sandstone with thin bands of dark red (2.5YR3/6) soft calcareous sandstone

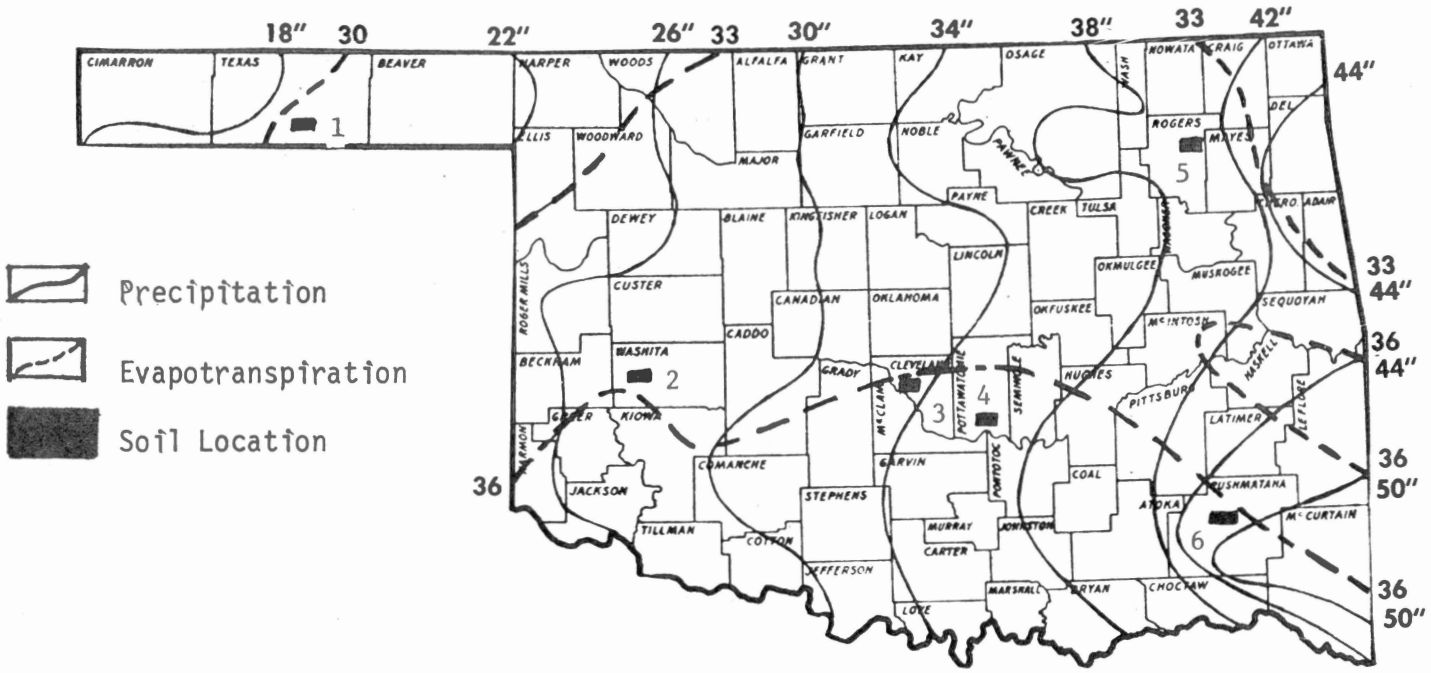


Figure 1. Mean Annual Precipitation Zones, Potential Evaporation Lines (Gray and Galloway, 1959), and Locations of the Pedons Sampled in Oklahoma.

1 - Ulysses, 2 - Dill, 3 - Aydelotte, 4 - Konawa, 5 - Dennis, 6 - Bernow

Methods

Soil samples were air dried and ground to pass through a 2 mm sieve. Cation exchange capacity was measured by the sodium saturation pH 8.2 method (Chapman, 1965). Bases were extracted by the 1N NH_4-acetate pH 7.0 procedure (Soil Survey Staff, 1972). Calcium and magnesium were determined by the 0.01N EDTA titration method of Richards (1954). Sodium and potassium were measured with a Perkin Elmer 403 atomic absorption spectrophotometer. Organic carbon was measured by the potassium dichromate oxidation method (Richards, 1954). Organic matter was estimated by multiplying the organic carbon value by a factor of 1.72. Exchangeable H was determined by the barium chloride triethanolamine procedure (Peech, 1965). Exchangeable Al was extracted by leaching with 1N KCl and measured by titration (Mclean, 1965). pH was measured in 1:1 water to soil and 1:1 1N KCl to soil mixture, using a Corning pH meter with a glass electrode.

Carbonates and organic matter content were removed from undisturbed soil samples by treatment with sodium acetate pH 5 and 30% H_2O_2 oxidation methods, respectively (Jackson, 1975). Soils were dispersed after washing several times with distilled water, using a shaker and a centrifuge. The soils were transferred into 1-liter sedimentation cylinders. Particle size distribution was determined using the hydrometer method. Clay-size fraction was siphoned to a depth determined by Stoke's Law (Kunze, 1965) into a 20-liter plastic container. The soil suspension was mixed again, and siphoning continued until sufficient clay was collected for analysis. The coarse (2-0.2 micron) and fine (less than 0.2 micron) clay fractions were separated using a Sharples

high speed steam turbine centrifuge as described by Jackson (1975). Clay samples were treated sequentially for dissolution of different components as follows:

1. Amorphous coatings and crystals of free iron oxides were removed by the citrate-dithionite-bicarbonate method of Mehra and Jackson (1960). Dissolved Fe, Al, and Si were determined using atomic absorption.

2. The amorphous clay component and alkali soluble silica and alumina were removed by boiling a K-saturated clay sample in 0.5N NaOH for 2.5 minutes in a nickel beaker, as described by Hashimoto and Jackson (1960). The amorphous material was based on SiO_2 plus Al_2O_3 dissolved with 10% water added. Additional treatment with the citrate-dithionite-bicarbonate procedure removed any iron oxides which might have been released from the dissolution of amorphous clay and free amorphous alumina and silica.

3. Hydroxy-Al and-Fe interlayers were removed from a powdered K-saturated clay sample which had already been washed one time with methanol, twice with 50% acetone in methanol, once with acetone, and finally air-dried from benzene. The sample was heated to 400°C for four hours, followed by 0.5N NaOH extraction, as described by Dixon and Jackson (1959, 1962). The Al and Si dissolved by treatments 2 and 3 were immediately measured colorimetrically by the molybdosilicate blue color (Kilmer, 1965) and aluminon method (Hsu, 1963), respectively. Released iron was removed by the dithionite method and determined with atomic absorption.

An oriented clay sample for X-ray diffraction analysis was prepared by addition of a clay suspension to a porous ceramic slide mounted

on a vacuum device for removal of excess moisture. X-ray diffraction patterns were obtained on a Ca-saturated sample, an ethylene glycol-solvated sample, a K-saturated sample, and a K-saturated sample heated to 550°C for four hours, using a General Electric XRD 6 instrument with Ni-filtered CuKα radiations at 30 KVP at 20 MA.

Results and Discussion

Physico-Chemical Properties

Calcium and magnesium were the major extractable bases for all soils (Table II). Sodium increased with depth in Dennis and Aydelotte soils; however, the amounts of and depth to sodium accumulations do not meet the requirements of a natric horizon. In the Bernow soil, leaching and weathering intensity are high, particularly in the subsoil which was low in bases and high in exchangeable aluminum and hydrogen. The other soils did not contain measurable amounts of exchangeable aluminum. Percent base saturation of the soils, except in Bernow and Dennis, was relatively high.

There were accumulations of carbonates in the subsoils of Ulysses, Aydelotte, and Dill. In Ulysses and Aydelotte soils, carbonate accumulations occurred in the B3 horizon. In the Dill soil, which is a relatively young soil, accumulations of carbonates occurred in the IIC horizon (Table II). Particle size distribution, chemical, and mineralogical analyses suggested the presence of a lithologic discontinuity between the B22 and C horizons of Dill.

The thickness of the dark colored surface horizons (23 cm) in Aydelotte did not allow that soil to be classified as a Mollisol. Particle

TABLE II

SELECTED CHEMICAL ANALYSES AND PARTICLE SIZE DISTRIBUTION OF STUDIED SOILS IN OKLAHOMA

Horizon	Depth	Percent			Ratio Fine/ Coarse	CEC Meq/	Extractable Cations Meq/100g					CEC/	Ca/	ESP	% Base Saturation		Percent	Percent	pH 1:1	
		Sand	Silt	Clay	Clay	100g	H	Ca	Mg	K	Na	AT	Clay	Mg		NaAc	Sum	OM	Carbonate	H_2O	KCl
	cm																				
Dennis																					
A1	0- 28	17.3	61.3	21.4	0.62	16.1	7.27	5.17	3.10	0.06	0.19	0.00	75.1	1.67	1.19	53.0	54.0	2.65	-	5.0	4.5
A3	28- 38	15.7	59.5	24.8	0.56	16.2	7.79	3.77	2.67	0.06	0.28	0.93	64.8	1.41	1.75	42.2	46.6	1.64	-	4.9	3.9
B21t	38- 53	7.9	41.4	50.7	-	34.5	13.75	8.82	7.63	0.14	1.20	1.06	68.1	1.16	3.48	51.5	56.4	1.67	-	5.0	4.0
B22t	53- 84	9.6	44.5	46.0	0.92	33.2	8.56	9.41	7.76	0.18	1.44	0.00	72.4	1.21	4.34	56.5	68.7	0.91	-	5.7	4.7
B23t	84-102	14.9	44.2	40.9	-	24.0	6.23	7.76	5.81	0.14	1.65	0.00	58.7	1.34	6.86	63.9	71.1	0.43	-	6.2	5.2
B31	102-147	13.1	39.5	47.4	0.43	26.9	6.75	8.31	6.11	0.13	2.31	0.00	56.7	1.36	8.62	62.6	71.4	0.48	-	5.9	4.9
B32	147-206	15.5	39.0	45.5	0.40	30.8	6.59	10.35	8.01	0.13	2.91	0.00	67.6	1.29	9.47	69.5	76.7	0.33	-	5.9	5.1
IICr	206-221	24.4	45.8	29.8	0.19	21.7	3.89	7.34	6.11	0.09	1.89	0.00	73.0	1.20	8.69	70.9	79.8	0.33	-	6.6	5.8
Bernow																					
A1	0- 13	58.9	35.5	5.7	0.20	8.8	2.84	3.56	1.14	0.14	0.04	0.00	154.8	3.11	0.40	55.6	63.2	2.34	-	6.5	5.7
A2	13- 25	39.2	36.4	4.4	0.17	4.6	1.70	2.25	0.34	0.05	0.03	0.00	103.0	6.63	0.68	58.4	41.9	1.13	-	6.6	5.7
B21t	25- 51	41.0	35.8	23.2	-	14.4	3.98	6.32	1.53	0.11	0.05	0.00	62.2	4.14	0.36	55.4	66.8	0.63	-	6.7	5.3
B22t	51- 97	37.5	41.8	20.7	0.32	14.4	8.53	1.90	1.91	0.11	0.07	2.50	69.4	1.00	0.49	27.8	31.9	0.33	-	4.9	3.6
B23t	97-142	42.6	39.1	18.4	0.45	13.2	9.38	1.06	1.10	0.11	0.07	2.45	72.1	0.96	0.53	17.7	20.0	0.35	-	5.0	3.5
B24t	142-203	41.6	40.9	17.6	-	10.2	7.96	1.15	1.19	0.11	0.21	4.04	58.0	0.96	2.06	26.0	25.0	0.25	-	5.0	3.5
Aydelotte																					
A1	0- 13	16.3	56.2	27.6	0.40	27.8	7.01	8.51	7.82	0.41	0.16	0.00	100.7	1.09	0.57	60.8	70.7	4.81	0.41	5.6	4.9
B1	13- 23	10.5	59.4	30.1	-	30.9	8.30	11.04	12.65	0.29	0.47	0.00	102.7	0.87	1.52	79.2	74.5	2.72	0.40	5.8	4.8
B21t	23- 53	8.0	48.2	43.8	0.65	37.0	6.49	11.50	17.48	0.32	1.13	0.00	84.6	0.66	3.05	82.2	82.4	1.61	1.82	6.5	5.5
B22t	53- 69	8.2	48.0	43.8	-	40.5	2.85	11.73	18.17	0.32	2.09	0.00	92.4	0.65	5.16	79.8	91.9	0.98	2.52	7.4	6.5
B23t	69-104	6.7	45.7	47.6	0.62	37.6	0.26	26.68	20.70	0.31	3.71	0.00	79.1	1.29	9.85	100.0	99.5	0.54	2.50	7.8	7.4
B24t	104-137	4.3	49.4	46.3	-	30.1	1.30	36.34	18.86	0.30	4.00	0.00	64.9	1.93	13.32	100.0	97.9	0.39	1.82	7.4	7.0
B31ca	137-175	4.3	53.7	42.0	0.16	29.5	0.78	50.60	17.48	0.24	3.79	0.00	70.2	2.89	12.86	100.0	98.9	0.30	13.02	7.7	7.1
B32ca	175-185	4.5	59.9	35.6	-	20.6	0.00	35.42	13.80	0.21	2.98	0.00	58.1	2.57	14.41	100.0	100.0	0.22	24.22	8.0	7.6
Cr	185-239	1.4	64.8	33.8	0.15	15.6	0.00	25.76	11.04	0.21	2.18	0.00	46.2	2.33	13.98	100.0	100.0	0.39	8.82	8.0	7.5
Konawa																					
AP	0- 15	66.3	27.4	6.3	0.34	3.4	2.27	1.93	0.71	0.16	0.04	0.00	53.9	2.71	1.30	84.0	55.6	0.80	-	6.4	5.8
A2	15- 36	63.1	31.9	5.0	0.31	3.0	1.71	1.89	0.67	0.21	0.04	0.00	60.3	2.81	1.44	92.3	62.2	0.51	-	6.3	5.8
B21t	36- 66	52.0	32.9	15.0	-	11.0	3.41	5.96	2.86	0.21	0.04	0.00	73.1	2.09	0.40	82.4	72.7	0.42	-	6.3	5.4
B22t	66- 97	56.2	32.5	11.3	0.85	8.3	2.84	4.49	2.52	0.16	0.04	0.00	73.1	1.78	0.53	87.3	71.7	0.30	-	6.2	5.5
B3	97-137	67.9	24.5	7.5	-	5.7	2.27	3.23	1.85	0.14	0.04	0.00	75.0	1.75	0.78	93.1	69.8	0.18	-	6.4	5.6
C	137-178	76.6	15.8	7.5	0.54	4.8	2.27	2.56	1.76	0.16	0.09	0.00	63.4	1.45	1.83	95.6	66.8	0.13	-	6.0	4.9
Ulysses																					
AP	0- 15	30.1	41.1	28.8	1.03	21.5	2.08	17.38	3.77	1.15	0.37	0.00	74.5	4.61	1.70	100.0	91.6	1.42	1.35	7.4	6.8
B1	15- 38	29.3	40.0	30.7	-	22.3	2.07	14.84	5.47	1.10	0.33	0.00	72.6	2.71	1.47	97.5	91.3	1.35	1.44	7.6	6.9
B2	38- 91	40.0	27.5	32.5	1.60	28.1	2.34	13.44	5.64	0.97	0.34	0.00	86.4	2.38	1.19	72.5	89.7	0.85	1.54	7.6	6.5
B3ca	91-122	20.3	46.5	31.0	-	25.6	0.00	44.10	7.34	1.05	0.37	0.00	77.1	6.01	1.46	100.0	100.0	0.63	8.15	8.1	7.2
Cca	122-163	42.7	30.4	26.9	0.91	21.7	0.00	42.82	4.41	1.07	0.33	0.00	80.5	9.71	1.52	100.0	100.0	0.47	5.26	8.0	7.1
Dill																					
A11	0- 10	56.8	30.6	12.6	-	14.7	1.71	7.98	3.44	0.59	0.09	0.00	116.6	2.32	0.59	82.1	87.6	1.96	1.00	6.8	6.2
A12	10- 36	55.9	29.2	14.9	1.10	12.9	0.85	7.10	2.94	0.38	0.09	0.00	86.4	2.41	0.68	81.3	92.5	1.26	0.92	6.8	5.8
B21	36- 53	56.0	27.0	17.0	1.30	14.4	0.85	8.11	3.78	0.21	0.09	0.00	84.7	2.14	0.61	84.3	93.5	0.99	1.10	6.9	5.9
B22	53- 84	54.1	29.1	16.8	-	14.7	1.14	8.27	4.03	0.21	0.09	0.00	87.0	2.05	0.60	85.9	91.7	0.90	1.20	7.3	6.0
IIC	84-119	52.2	35.6	12.2	0.60	12.6	0.00	29.06	5.04	0.13	0.09	0.00	103.0	5.77	0.69	100.0	100.0	0.15	14.85	8.4	7.6

size analysis showed an illuviation of clay into the B horizon of Ulysses and Dill soils. This was also indicated by the fine-to-coarse clay ratio. However, the increase in the clay content of the B horizon was not sufficient to indicate an argillic horizon in either soil. Argillic horizons, however, were present in the other soils. Bernow and Konawa soils had conspicuous eluvial or A2 horizons. Lower parts of the argillic horizon in Bernow contained about 10% streaks and pockets of the eluvial horizon. Organic matter content decreased with depth in all soils. Beginning with the most leached, the soils studied may be ranked as Bernow, Dennis, Konawa, Aydelotte, Dill, and Ulysses.

Distribution of Free Iron Oxides

Citrate-dithionite-bicarbonate treatment removed small amounts of alumina and silica from the coarse and fine clay fractions in addition to free iron oxides (Tables III and IV). Large quantities of these oxides might have derived from the contaminant materials associated with the iron oxides coating the surface of the clays. Larger amounts of alumina were extracted from the fine clays. Extractable alumina and silica were generally present in larger amounts in the surface horizons. This treatment might have also removed some Al and Fe from the interlayer spaces of 2:1 expansible clay minerals. Dennis and Ulysses soils contained, respectively, the largest and smallest amounts of free iron oxides. Coarse clays of Dennis, Bernow, and Konawa soils, which are highly leached, contained higher concentrations of free iron oxides in the B horizons. The A2 or A3 horizons of these soils contained the smallest amounts of iron oxides. This is due mainly to eluviation. However, iron oxides in the fine clay fractions did not show similar

TABLE III

SiO_2, Al_2O_3, and Fe_2O_3 DISSOLVED FROM THE COARSE CLAY FRACTION BY SEQUENTIAL TREATMENTS

Horizon	Treatment 1 Citrate-dithionite-bicarbonate			Treatment 2 0.5 N NaOH			Treatment 3 Preheated at 400°C and 0.5 N NaOH		
	SiO_2	Al_2O_3	Fe_2O_3	SiO_2	Al_2O_3	Fe_2O_3	SiO_2	Al_2O_3	Fe_2O_3
	%								
Dennis									
A1	1.6	1.0	4.5	5.1	1.9	0.5	1.7	1.3	0.2
A3	1.1	1.1	4.0	3.9	1.8	0.4	1.1	1.0	0.2
B22t	1.6	1.7	6.1	5.5	3.0	0.6	1.5	1.2	0.2
B31	1.4	1.4	5.8	5.6	3.2	0.7	0.3	0.5	0.1
B32	1.3	1.4	6.1	3.8	2.1	0.6	0.8	0.7	0.1
IICr	1.2	0.6	3.8	1.4	0.8	0.3	0.1	0.1	0.0
Bernow									
A1	1.4	1.1	4.2	4.5	2.5	0.4	1.6	1.7	0.1
A2	1.1	1.1	3.2	4.7	2.7	0.5	1.3	1.2	0.1
B22t	1.0	1.5	4.3	5.1	2.1	0.6	1.3	1.1	0.1
B24t	1.4	1.2	5.3	4.1	2.3	0.4	1.1	1.0	0.1
Aydelotte									
A1	1.9	1.0	3.8	4.8	2.3	0.8	2.7	2.3	0.3
B21t	1.2	1.0	3.7	3.5	1.9	0.6	2.0	2.6	0.4
B23t	1.7	0.8	3.6	3.3	1.7	0.4	1.3	1.0	0.1
B31ca	1.1	0.4	2.3	2.4	0.9	0.3	0.7	0.5	0.0
Cr	1.5	0.3	2.9	1.9	0.7	0.4	0.2	0.1	0.0
Konawa									
AP	1.6	0.6	3.9	3.9	1.9	0.5	0.7	1.4	0.1
A2	1.2	0.7	3.3	4.3	2.0	0.6	0.5	1.3	0.1
B21t	1.7	1.0	4.1	6.0	3.0	0.7	1.0	1.2	0.1
C	2.0	1.0	4.4	6.9	3.5	0.8	0.7	1.0	0.1
Ulysses									
AP	1.2	0.5	2.5	5.5	1.5	1.0	2.3	1.4	0.3
B2	1.1	0.4	2.8	4.7	1.4	0.8	1.8	1.3	0.2
Cca	1.0	0.3	2.2	3.5	1.1	0.6	0.3	0.8	0.1
Dill									
A12	1.9	1.2	4.3	4.2	1.6	0.3	0.8	1.2	0.1
B21	1.7	1.0	3.7	3.4	1.6	0.4	0.7	1.1	0.1
IIC	1.2	0.5	4.3	1.2	0.4	0.2	0.1	0.7	0.1

TABLE IV

SiO_2, Al_2O_3, AND Fe_2O_3 DISSOLVED FROM THE FINE CLAY FRACTION BY SEQUENTIAL TREATMENTS

Horizon	Treatment 1 Citrate-dithionite-bicarbonate			Treatment 2 0.5 N NaOH			Treatment 3 Preheated at 400°C and 0.5 N NaOH		
	SiO_2	Al_2O_3	Fe_2O_3	SiO_2	Al_2O_3	Fe_2O_3	SiO_2	Al_2O_3	Fe_2O_3
	%								
Dennis									
A1	2.0	1.8	4.7	6.5	3.0	1.1	6.6	4.4	0.9
A3	1.8	2.4	6.0	6.5	3.0	1.0	8.8	5.7	0.9
B22t	1.5	1.9	5.8	6.6	3.2	0.8	6.3	4.8	0.8
B31	1.8	1.7	5.9	6.9	3.5	0.7	5.0	4.1	0.7
B32	1.6	1.5	5.0	5.2	2.9	0.8	2.6	1.9	0.4
IICr	1.7	1.1	4.0	4.2	2.1	0.8	0.1	0.8	0.1
Bernow									
A1	1.8	2.4	5.4	6.9	3.9	0.7	3.2	2.7	0.2
A2	1.6	2.4	5.3	6.1	3.4	0.6	7.4	5.3	0.3
B22t	1.5	2.7	4.4	6.2	3.2	0.5	6.2	4.4	0.3
B24t	2.0	2.1	4.5	6.1	3.1	0.6	4.1	2.8	0.2
Aydelotte									
A1	2.0	1.4	3.6	4.7	1.8	0.8	5.5	3.3	0.6
B21t	1.5	1.4	3.0	4.8	2.2	0.8	5.3	3.2	0.6
B23t	1.3	0.9	3.0	4.7	2.0	0.7	2.6	1.9	0.1
B31ca	1.3	0.9	4.8	2.9	1.1	0.4	1.6	1.3	0.1
Cr	1.4	0.5	5.8	1.8	0.6	0.2	0.9	0.3	0.1
Konawa									
AP	2.2	1.4	4.3	5.3	2.7	0.7	7.4	4.8	0.7
A2	1.7	1.5	4.4	8.2	4.2	1.0	1.8	1.0	0.4
B21t	1.4	1.3	3.6	6.9	3.9	0.9	3.2	2.3	0.3
C	1.5	1.4	4.2	9.8	5.5	1.0	0.6	0.2	0.2
Ulysses									
AP	2.4	0.8	1.9	4.6	1.7	0.9	7.2	3.8	0.5
B2	1.9	0.7	1.6	4.6	1.6	1.0	8.4	4.8	0.9
Cca	1.5	0.6	1.4	4.2	1.6	0.9	4.9	2.6	0.4
Dill									
A12	1.6	1.1	4.8	3.9	1.8	0.4	5.9	3.1	0.3
B21	1.5	1.1	4.9	3.2	1.7	0.3	6.2	2.9	0.1
IIC	2.1	0.5	11.6	1.8	0.6	0.2	0.7	0.4	0.1

distribution patterns. Coarse clays in the Aydelotte soil contained a higher concentration of iron oxides in the surface horizons, while fine clays showed the highest concentration in the B31 and Cr horizons. Ulysses and Dill soils showed a relatively uniform distribution pattern for iron oxides in both coarse and fine clay. Fine clay in the IIC horizon of Dill contained 11% iron oxides compared to 4.9% for the B21 horizon. This difference is due to the lithologic discontinuity found in this particular soil.

Distribution of Amorphous Clay

Boiling clays for 2.5 minutes in 0.5N NaOH removed slightly larger amounts of silica and alumina from the Dennis, Bernow, and Konawa soils than the others (Table V). The amount of iron removed by this treatment was small and suggested alumina and silica were the major components of the alkali-soluble amorphous clays. Amorphous clays decreased with depth in both the coarse and fine clay fractions of Aydelotte and Dill soils. The partially weathered shale and sandstone underlying these soils contained the smallest amounts. The alluvium and loess deposits in which Ulysses and Konawa are respectively developed, contained relatively larger amounts of amorphous clays. Amorphous clays, however, did not constitute a larger portion of the clay in any of the soils studied. The SiO_2 to Al_2O_3 molar ratios of dissolved aluminosilicates were equal to or greater than 3.0 in all soils (Table V). This indicated that the amorphous clays were highly siliceous aluminosilicates or montmorillonitic-like clay minerals. Amorphous clays were generally present in greater amounts in the fine clay fractions; however, Ulysses and Dill soils, which are relatively younger, contained the same amounts

TABLE V

AMORPHOUS ALUMINOSILICATES IN THE COARSE AND FINE CLAY FRACTIONS

Horizon	Coarse Clay		Fine Clay	
	Amorphous	SiO_2/Al_2O_3	Amorphous	SiO_2/Al_2O_3
	%	Molar	%	Molar
		Dennis		
A1	7.8	4.6	10.5	3.7
A3	6.3	3.7	10.6	3.7
B22t	9.4	3.1	10.9	3.5
B31	9.8	3.0	11.5	3.4
B32	6.6	3.1	9.0	3.0
IICr	2.4	3.0	7.0	3.4
		Bernow		
A1	7.8	3.1	12.0	3.0
A2	8.2	3.0	10.5	3.1
B22t	8.0	4.1	10.4	3.3
B24t	7.1	3.0	10.2	3.4
		Aydelotte		
A1	7.9	3.5	7.3	4.4
B21t	6.0	3.1	7.8	3.7
B23t	5.5	3.3	7.4	4.0
B31ca	3.7	4.5	4.4	4.5
Cr	2.9	4.6	2.7	5.1
		Konawa		
AP	6.4	3.5	8.9	3.3
A2	7.0	3.7	13.8	3.3
B21t	10.0	3.4	12.0	3.0
C	11.5	3.3	17.0	3.0
		Ulysses		
AP	7.7	6.2	7.0	4.6
B2	6.8	5.7	6.9	4.9
Cca	5.1	5.4	6.5	4.5
		Dill		
A12	6.5	4.5	6.3	3.7
B21	5.5	3.6	5.4	3.2
IIC	1.8	5.1	2.7	5.1

in the coarse and fine clay fractions.

Distribution of Hydroxy-Al and-Fe Interlayers

Heating of clay samples at 400°C for four hours and subsequent extraction with 0.5N NaOH removed larger amounts of Al from the fine clay fraction. However, most of the Al removed from the fine clays originated from the destruction of the fine clay structure by the 400°C heating treatment. Destruction of fine clays was clearly demonstrated by large amounts of dissolved silica (Table IV). However, the destructive effect was relatively minor on the fine clay fractions of subsoils and parent materials. Small amounts of dissolved Fe indicated the absence of significant amounts of Fe in the interlayer space. Greater amounts of Fe were removed from the fine clays, particularly in Dennis, Konawa, and Ulysses soils. This may also be due to the collapse of the fine clay structure by 400°C heating. Larger amounts of Al were extracted from the coarse clay fractions of the surface horizons of the soils studied (Table III). X-ray diffraction analysis showed the presence of larger amounts of interlayered 2:1 expansible clay minerals in the upper horizons. Intensive weathering, wetting and drying cycles, and moderate acidity are the major contributing factors in the formation of Al-interlayers in the surface horizons. Rich (1968) suggested that wetting and drying cycles may favor the formation of the interlayers in the A over the B horizon; however, the B horizon may be favored by smaller amounts of organic matter. Although pH is an influential factor in the formation of Al-interlayer, intermediate amounts of Al were removed from the coarse clay fraction of the A and B horizons of the Ulysses soil, which has high pH values (Table II). However, the

dissolved silica (Table III) showed a greater destructive effect of the 400°C heating treatment on the coarse clay fraction of Ulysses and Aydelotte soils. This could have contributed to the amounts of Al removed from the coarse clay fraction in those soils. The presence of small amounts of interlayer materials was shown in the coarse clay fraction of the IIC horizon of the Dill soil. The 15 Å d-spacing clay mineral expanded due to solvation with ethylene glycol, as shown by the sharp 17.7 A peak. However, the broad, asymmetric 10 Å peak suggested that the expanding clay mineral or montmorillonite did not collapse completely to 10 Å due to 550°C heating of the K-saturated sample. The IIC horizon of Dill had a pH value of 8.4, and the amount of Al_2O_3 removed from the coarse clay fraction was not large (0.7%). Greater amounts of Al were removed from the coarse and fine clay fractions of the A12 and B21 horizons in the Dill soil. X-ray diffraction also showed the presence of interlayered montmorillonite in the Ulysses soil which is developed in calcareous loess. The pH values in this soil profile ranged from 7.4 in the AP to 8.1 in the C horizon. Hydroxy-Mg is usually the most active interlayering material in the alkaline condition (Rich, 1968). The coarse and fine clay fractions of the shaly parent material underlying the Aydelotte soil showed a 14 Å peak for chlorite after K-saturation and heating at 550°C. This peak was probably due to the presence of trioctahedral Mg-chlorite because Al and Fe interlayers were not present in significant amounts (Tables III and IV). The presence of trioctahedral chlorite was also supported by an increase in the intensity of the 14 Å A peak due to 550°C heating of the K-saturated sample. X-ray diffraction showed a weakened 14 Å peak for chlorite in the A1 horizon of the Aydelotte soil. Therefore, under a

low degree of weathering and alkaline conditions (pH 8.0), chlorite has persisted (Jackson, 1963). Large quantities of chlorite in the Al horizon, however, could have been transformed to vermiculite and finally to montmorillonite as the chlorite was gradually exposed to intensive weathering.

The formation of a greater amount of interlayer materials in the coarse clay fraction suggested that interlayering may be preferentially formed in vermiculite rather than montmorillonite (Dixon and Jackson, 1962). The higher layer charge of vermiculite than of montmorillonite probably favors the formation of larger amounts of Al in the interlayer space of vermiculite. Larger amounts of chloritized clay minerals in the upper soil profile and the coarse clay fraction suggested that they are residual materials developed due to increased resistance to decomposition as compared to normal expansible clay minerals (Jackson, 1963; Weed and Nelson, 1962). Jackson (1963) suggested that interlayered clays developed either by precipitation of hydroxy-Al attached on one interlayer surface of montmorillonite, "18 Å swelling intergrade," or on two interlayer surfaces of vermiculite, "14 Å intergrade." The 18 Å intergrade is likely to form more frequently in alkali soils in which montmorillonite is more stable, while the 14 Å intergrade is usually found in acid soils in which the following equations (Jackson, 1963) are favored:

$$\text{mica} \rightleftharpoons \text{vermiculite} \rightleftharpoons \text{14 Å intergrade}$$

X-ray diffraction showed the occurrence of similar situations in the soils studied. The 2:1 layer clay minerals in Dill and Ulysses soils expanded to 17-18 Å due to solvation with ethylene glycol.

However, the asymmetric 10 Å peak indicated that montmorillonite did not collapse completely to 10 Å due to 550°C heating of the K-saturated specimen. The author also found a similar situation in many other soils in western Oklahoma. On the other hand, the expansible clay minerals in Bernow and Konawa soils, particularly in the coarse clay fraction, did not expand completely due to ethylene glycol solvation and collapsed only partially to 10 Å due to K-saturation and heating at 550°C.

Although 0.5N NaOH extraction did not show a marked difference in the amount of Al-interlayers in the coarse clay fraction of the soils studied, X-ray diffraction analysis suggested relatively larger amounts of intergrade clay minerals in the surface horizons of Dennis, Bernow, and Konawa soil.

Due to the destructive effect of 400°C heating on the fine clay fraction, determination of the amounts of Al occupying the interlayer space was not possible. However, the occurrence of asymmetric 10 Å peaks in most 550°C heated samples suggested a partial filling of the interlayer space. The fine clay fraction showed somewhat uniform distribution patterns for interlayer materials in the soil profile. Future studies of interlayer materials by the procedure employed herein in Oklahoma soils should use a lower temperature for fine clays due to the destruction of disorderly crystalline clays by heating to 400°C.

CHAPTER III

QUANTITATIVE DETERMINATION OF CLAY MINERALS IN SELECTED OKLAHOMA SOILS

Determination of the kinds and relative amounts of clay minerals is necessary to more fully understand soil physico-chemical properties such as shrink-swell potential, cation exchange capacity, K reserve and release rates, K and NH_4 fixation potential, and intensity of weathering factors to which soils have been exposed. Knowledge of soil clay minerals is also needed for placing soils with more than 35% clay content into the correct family classes according to Soil Taxonomy (Soil Survey Staff, 1975). The main objective of this work was to study the distribution patterns of clay minerals in six Oklahoma soils formed in materials of five geologic ages under a wide range of climatic conditions.

Gray et al. (1963) studied clay minerals of selected Oklahoma soils and reported that montmorillonite and illite were the dominant. clay minerals with lesser amounts of vermiculite and kaolinite. Wilkinson and Gray (1954) studied clay minerals of certain reddish prairie soils and estimated their montmorillonite and illite content. Fanning and Gray (1959) studied the clay mineral content of a Parsons and a Dennis soil in eastern Oklahoma. Culver and Gray (1968) investigated weathered and unweathered redbeds and shales of the Wellington formation of Permian age. They found illite to be the dominant clay mineral in

the formation. Stahnke (1968) studied the clay minerals of several Pedons located on terrace deposits of the South Canadian River in west central Oklahoma.

Materials and Methods

Locations, parent materials, and classifications of the soils studied are reported in Table VI.

Soil samples were air dried. Carbonates and organic matter were removed by treatment with NaOAC-HOAC pH 5 and 30% H_2O_2 oxidation methods, respectively (Jackson, 1975). Free iron oxides were removed by the dithionite-citrate-bicarbonate method of Mehra and Jackson (1960). Soils were dispersed after washing several times with distilled water and application of a sonic vibrator. The soils were transferred into 1-liter sedimentation cylinders. The clay fraction was siphoned to a depth determined by Stokes Law (Kunze, 1965) into a 20-liter plastic container. Siphoning was continued until sufficient clays were collected for analysis. The coarse (2-0.2 micron) and fine (less than 0.2 micron) clay fractions were separated with a Sharples high speed steam turbine centrifuge, as described by Jackson (1975). An NH_4-saturated clay sample was freed from water by washing once with methanol, twice with 50% acetone in methanol, and once with acetone. It was finally air-dried from benzene to prevent aggregation. The loose, fluffy clay was dried at 110°C, weighed, and total K was determined by the HF-$HClO_4$ method (Jackson, 1968). Potassium was measured with a Perkin Elmer 403 atomic absorption spectrophotometer (Table VIII). Illite was calculated based on 10% K_2O for the mineral structure (Jackson and Mackenzie, 1964). Because appreciable amounts of feldspars were not detected by

TABLE VI

LOCATIONS, PARENT MATERIALS, AND CLASSIFICATIONS OF THE SOILS STUDIED

Soil	County	Climate	Parent Material	Soil Classification
Dennis	Rogers	humid AP‡102 cm	reworked shale of Pennsylvanian age	fine, mixed, thermic Aquic Paleudoll
Bernow	Pushmataha	humid AP 119 cm	weakly cemented sandstone of Cretaceous age	fine-loamy, siliceous, thermic typic Paleudult
Aydelotte	Cleveland	moist subhumid AP 84 cm	alternating layers of red shale and siltstone of Permian age	fine, mixed, thermic Udertic Paleustalf
Konawa	Pottawatomie	moist subhumid AP 94 cm	sandy old alluvium of Quaternary age	coarse-loamy, mixed, thermic Ultic Haplustalf
Ulysses	Texas	semi-arid AP 48 cm	highly calcareous wind laid silt (loess) of Tertiary age	fine-loamy, mixed, thermic Aridic Haplustoll
Dill	Washita	dry subhumid AP 68 cm	weakly cemented noncalcareous sandstone of Permian age	coarse-loamy, mixed, thermic Udic Ustochrept

‡Mean annual precipitation

X-ray diffraction analysis, no correction was made for K_2O in the K-feldspar. Amorphous clay was determined by boiling a K-saturated clay sample in 0.5N NaOH for 2.5 minutes, as described by Hashimoto and Jackson (1960). Kaolinite content was determined on a K-saturated clay sample after amorphous aluminosilicates and interlayer minerals were removed (Dixon and Jackson, 1959, 1962). The sample was heated to 550°C for four hours and powdered. Then it was boiled in 0.5N NaOH for 2.5 minutes in a nickel beaker (Jackson, 1975) followed by extraction of released iron oxides by the dithionite-citrate-bicarbonate method. Dissolved Al and Si were measured colorimetrically by the molybdosilicate blue color (Kilmer, 1965) and aluminon methods (Hsu, 1963), respectively. Extracted Fe was determined by atomic absorption. Kaolinite plus halloysite was calculated based on SiO_2/Al_2O_3 molar ratios of dissolved aluminosilicates (Table VII) as described by Alexiades and Jackson (1966). Soil vermiculite and montmorillonite were determined by the method of Alexiades and Jackson (1965) discussed briefly below. The cation exchange capacity (CaEC) of a clay sample was determined by saturating the sample with Ca^{++} using 1N $CaCl_2$ as the saturating solution and then replacing the Ca^{++} by Mg^{++} using 1N $MgCl_2$ as the extracting solution. The K fixation capacity (K/EC) of the clay sample was determined by saturating the sample with K^{+} using 1N KCl. The K-saturated sample was heated to 110°C overnight, and the remaining exchangeable K was replaced by NH_4^{+} using 1N NH_4Cl. Ca and K were measured using atomic absorption. Vermiculite and montmorillonite content were estimated from the CaEC, K/EC (Table VIII) and the amorphous material with a SiO_2/Al_2O_3 molar ratio of greater than 3.0 (Table VII).

An oriented clay sample for X-ray analysis was prepared by

TABLE VII

DISSOLVED SiO_2, Al_2O_3, AND Fe_2O_3 FROM CLAY SAMPLES FROM WHICH AMORPHOUS CLAYS AND HYDROXY INTERLAYERS WERE PREVIOUSLY REMOVED

Horizon	Coarse Clay				Fine Clay			
	SiO_2	Al_2O_3	Fe_2O_3	SiO_2/Al_2O_3	SiO_2	Al_2O_3	Fe_2O_3	SiO_2/Al_2O_3
	%			Molar	%			Molar
Dennis								
A1	7.78	5.48	0.18	2.41	8.98	5.57	0.54	2.74
A3	7.02	4.95	0.30	2.41	9.43	4.24	0.32	3.78
B22t	11.84	8.12	0.49	2.48	9.40	4.63	0.47	3.45
B31	12.71	9.32	0.33	2.32	9.98	4.29	0.34	3.55
B32	10.89	8.70	0.20	2.12	6.69	4.33	0.44	2.62
IICr	10.66	8.83	0.12	2.05	5.48	3.68	0.30	3.06
Bernow								
A1	13.04	8.32	0.27	2.66	11.33	7.20	0.85	2.67
A2	12.53	8.79	0.25	2.42	11.69	8.19	0.86	2.42
B22t	16.80	11.68	0.25	2.44	11.96	7.37	0.76	2.76
B24t	16.79	11.95	0.34	2.39	12.63	8.78	0.72	2.44
Aydelotte								
A1	8.75	5.37	0.45	2.77	7.80	5.11	0.48	2.59
B21t	8.86	5.59	0.41	2.69	6.08	4.63	0.49	2.37
B23t	7.95	5.00	0.47	2.70	5.76	5.54	0.63	1.76
B31ca	5.26	4.06	0.43	2.20	3.64	2.30	0.58	2.69
Cr	6.57	4.76	0.46	2.35	3.40	3.40	0.40	1.70
Konawa								
AP	7.84	5.84	0.43	2.28	9.51	4.58	0.53	3.52
A2	7.82	5.52	0.33	2.41	8.76	5.44	0.61	2.73
B21t	10.97	8.00	0.58	2.33	9.47	4.91	0.55	3.28
C	9.81	7.72	0.21	2.16	8.58	5.53	0.11	2.63
Ulysses								
AP	6.20	5.00	0.15	2.11	6.14	2.88	0.58	3.62
B2	7.53	4.12	0.22	2.69	5.48	2.95	0.56	3.15
Cca	5.62	3.43	0.13	2.78	5.57	2.26	0.80	4.18
Dill								
A12	6.58	4.73	0.15	2.36	6.79	2.98	0.40	3.87
B21	6.23	4.01	0.21	2.64	6.38	2.89	0.60	3.76
IIC	2.91	1.37	0.13	3.61	1.78	0.67	0.21	4.51

TABLE VIII

CaEC, K/EC, AND K_2O% IN COARSE AND FINE CLAY FRACTIONS OF THE SOILS STUDIED

Horizon	Coarse Clay			Fine Clay		
	CaEC	K/EC	K_2O	CaEC	K/EC	K_2O
	Meq/100g		%	Meq/100g		%
Dennis						
A1	38.2	22.3	2.43	73.8	62.3	1.62
A3	26.1	16.8	2.31	68.9	63.9	1.63
B22t	45.1	33.5	2.00	74.2	68.0	1.79
B31	39.1	24.9	2.65	62.5	58.1	2.37
B32	47.6	25.4	3.16	68.0	57.0	3.15
IICr	32.0	14.0	4.97	55.4	42.4	4.60
Bernow						
A1	32.4	23.4	2.46	59.8	51.7	1.80
A2	28.3	22.1	2.26	60.2	52.8	1.78
B22t	42.5	31.0	2.25	61.0	50.4	1.61
B24t	37.9	24.1	2.70	61.6	49.9	1.97
Aydelotte						
A1	56.6	44.2	3.45	79.3	74.0	1.46
B21t	59.2	43.2	3.33	84.3	73.9	1.21
B23t	55.4	38.5	3.23	77.2	64.0	1.84
B31ca	54.9	37.5	3.90	68.7	57.2	2.58
Cr	39.1	30.0	4.50	57.0	53.0	3.63
Konawa						
AP	29.8	21.4	4.47	64.1	61.2	2.92
A2	30.2	21.9	3.62	65.8	64.0	2.38
B21t	55.2	40.5	2.95	70.7	68.0	2.20
C	45.2	33.1	3.68	63.8	61.5	2.46
Ulysses						
AP	47.0	41.2	3.59	84.5	77.4	1.39
B2	41.2	33.5	3.99	88.0	84.7	1.30
Cca	33.6	27.8	4.58	86.2	79.0	1.18
Dill						
A12	63.0	49.9	3.41	88.1	80.3	1.41
B21	64.7	47.2	3.54	92.0	81.8	1.34
IIC	85.8	64.6	2.44	84.0	79.0	2.18

addition of a clay suspension to a porous ceramic slide mounted on a vacuum device for removal of excess moisture. X-ray diffraction patterns of the coarse and fine clay fractions were obtained from Ca-saturated, ethylene glycol-solvated, K-saturated, and 550°C heated K-saturated samples using a General Electric XRD 6 instrument with Ni-filtered CuKα radiations generated at 30 KVP and 20 MA.

Results and Discussion

X-ray Diffraction Analysis

X-ray diffraction patterns for the coarse and fine clay fractions of the A, B, and C horizons of the soils studied are shown in Figures 2 through 7.

In the Dennis soil (Figure 2), discrete illite was identified in the coarse clay fractions by peaks at 10 and 5 Å. A diffuse peak at 10 Å in the A1 horizon indicated weathering of illite at the soil surface. The fine clay fractions in the A1 and B22t horizons did not show peaks for discrete illite. The 15 Å d-spacing clay mineral in the coarse clay fractions of the A1 and B22t horizons partially expanded due to solvation with ethylene glycol; and due to 550°C heating of a K-saturated sample, it collapsed to 10 Å, as shown by a 10 Å asymmetric peak. This suggested the presence of interlayered 2:1 expansible clay minerals in the coarse clay fractions of these horizons. Montmorillonite was identified in the fine clay fractions of the A1 and B22t horizons by a broad, intense peak at 17-18 Å in the ethylene glycol-solvated specimen. The fine clay of the IICr horizon showed a diffuse, intense peak at 11.62 Å which shifted to 14 Å due to ethylene glycol

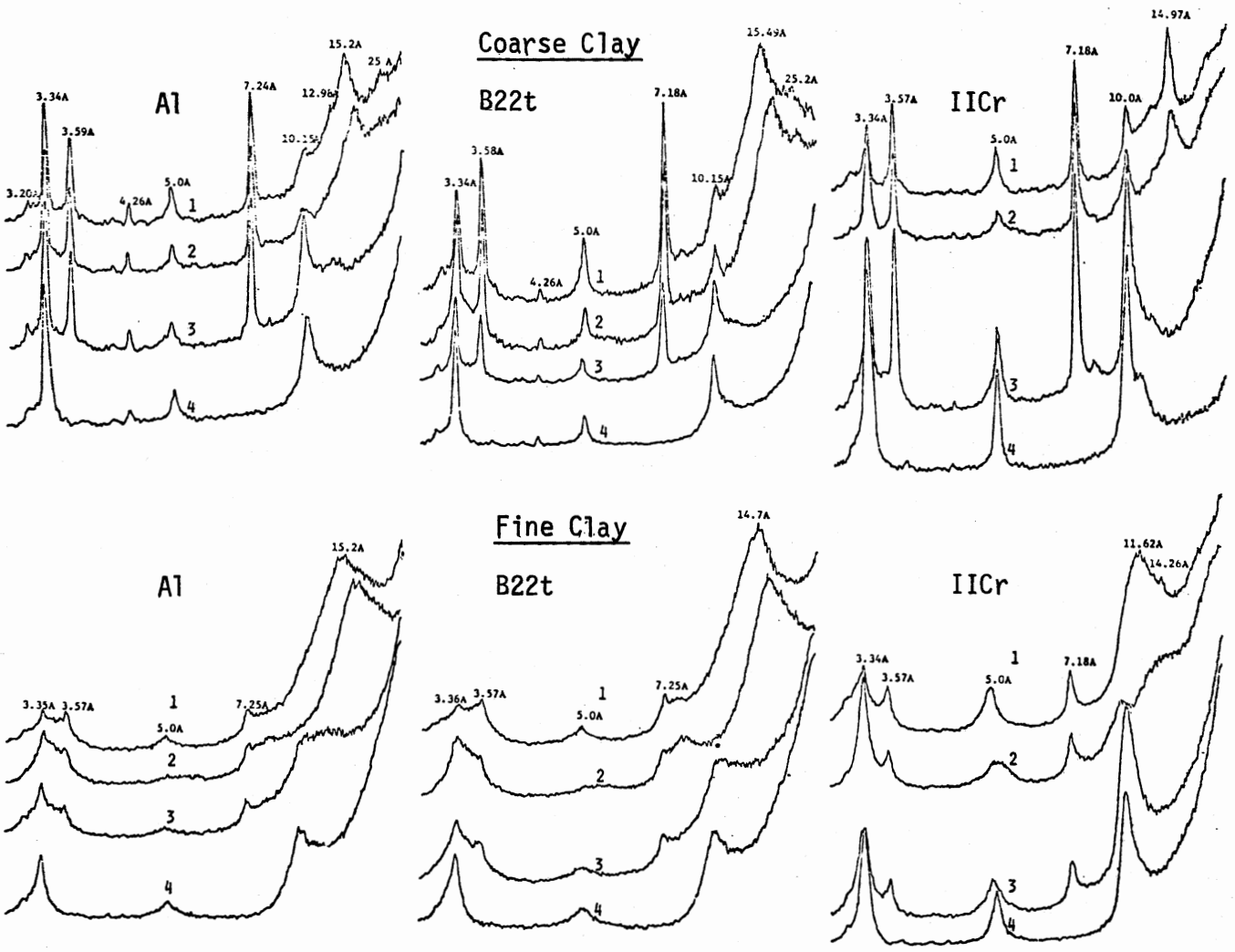


Figure 2. X-ray Diffractograms for the Dennis Soil Showing Patterns for the Coarse and Fine Clay Fractions in the A1, B22t, and IICr Horizons: (1) Ca-saturated, (2) Ethylene Glycol-solvated, (3) K-saturated, and (4) 550°C Heated K-saturated

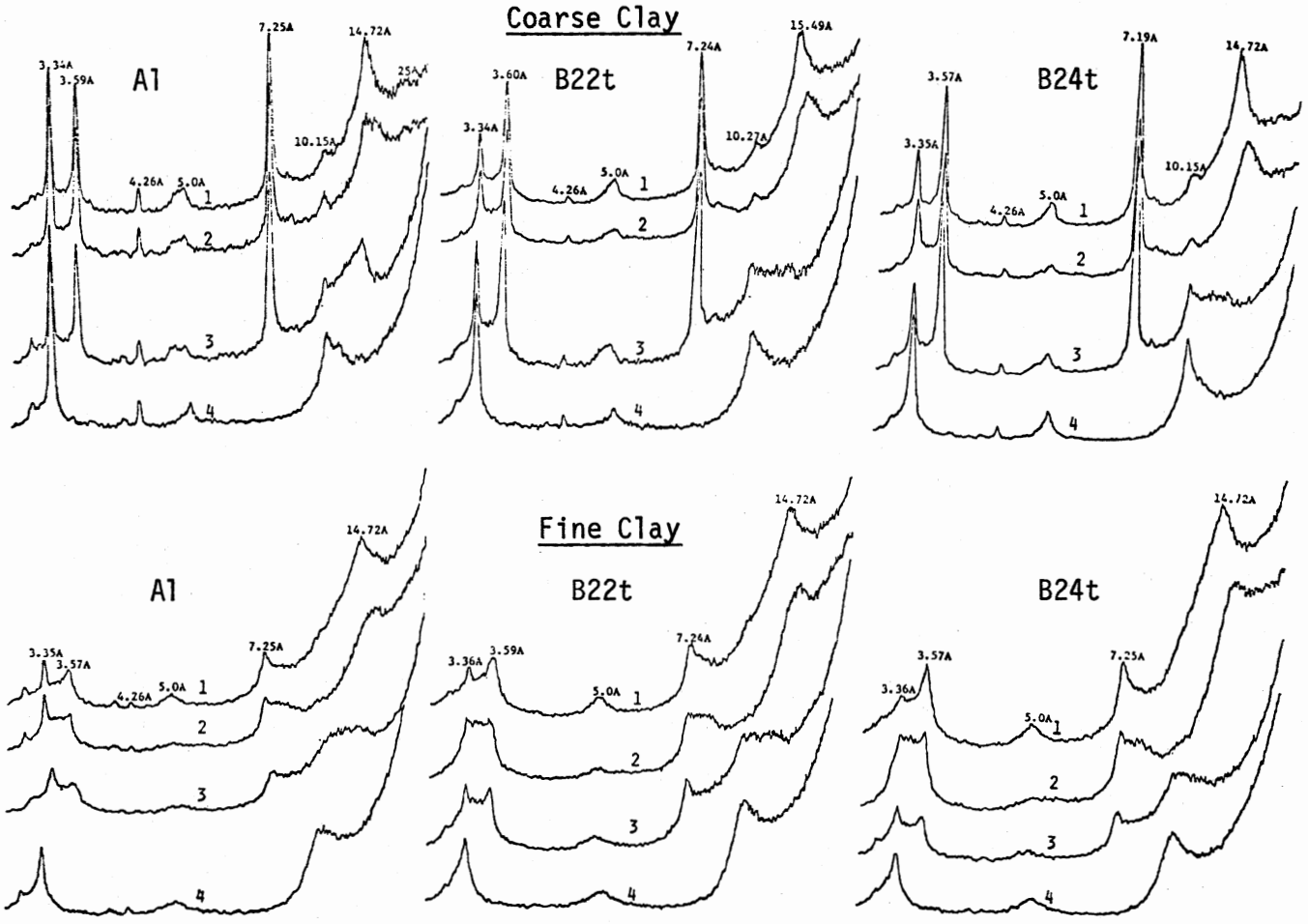


Figure 3. X-ray Diffractograms for the Bernow Soil Showing Patterns for the Coarse and Fine Clay Fractions in the A1, B22t, and B24t Horizons

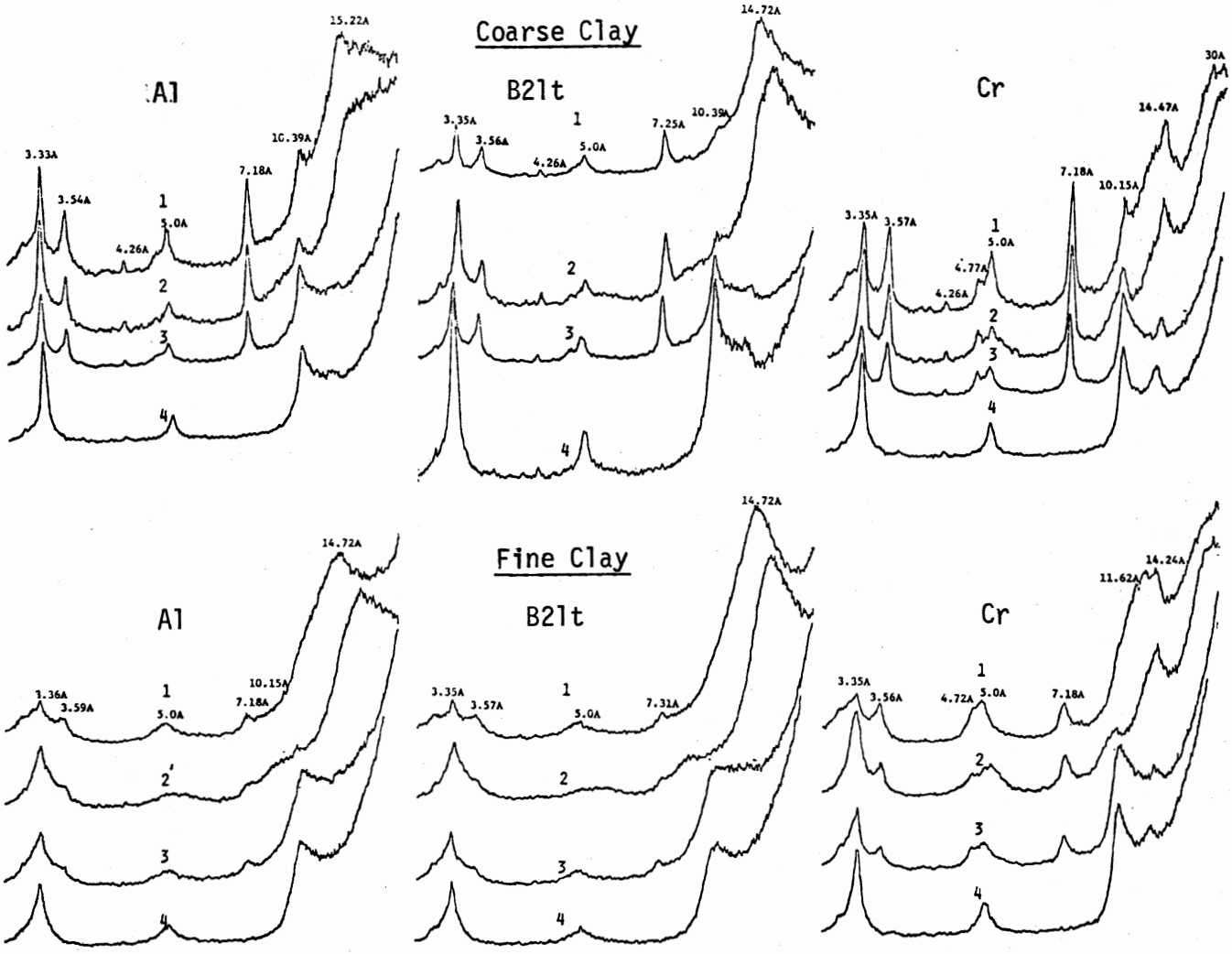


Figure 4. X-ray Diffractograms for the Aydelotte Soil Showing Patterns for the Coarse and Fine Clay Fractions in the A1, B21t, and Cr Horizons

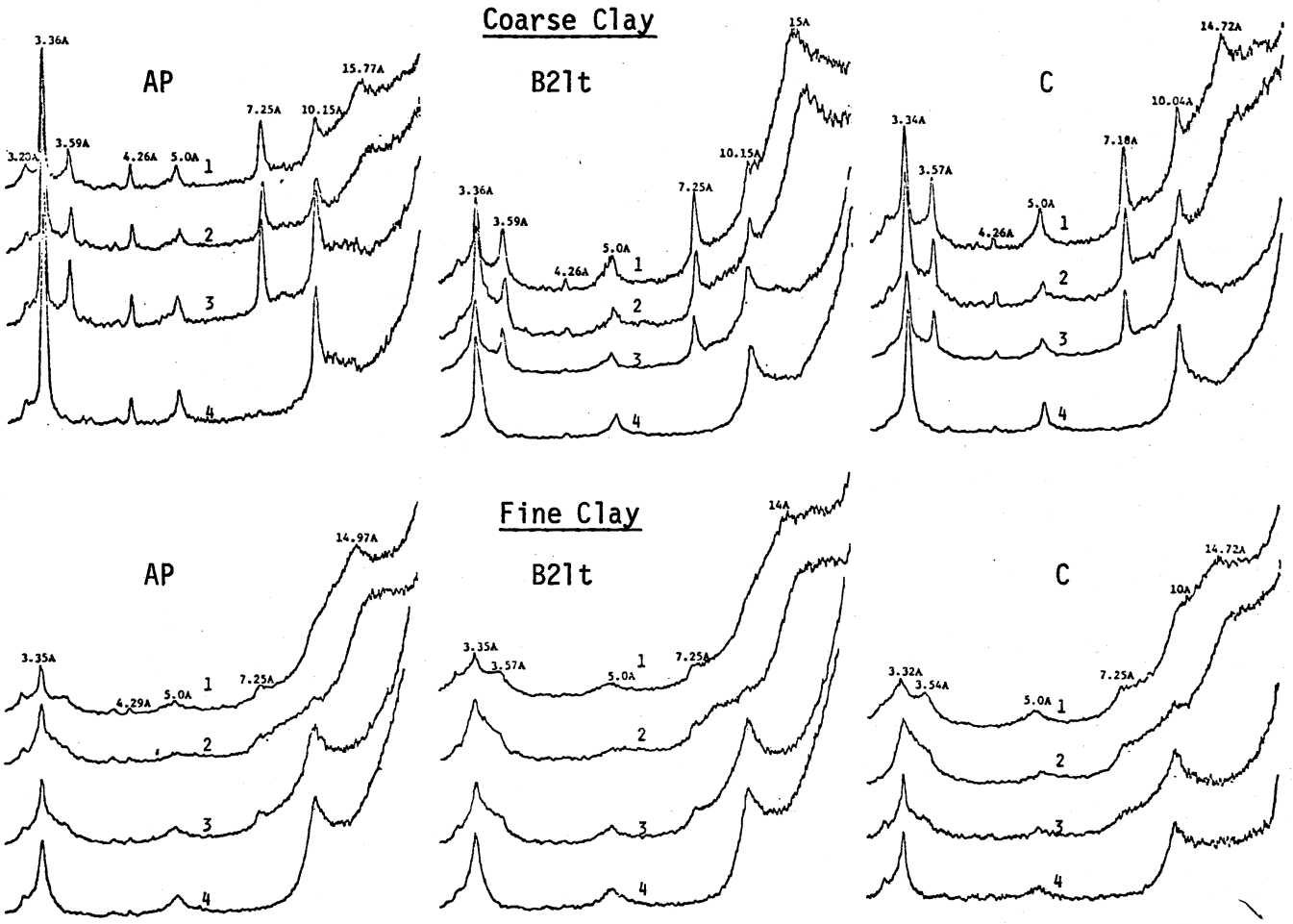


Figure 5. X-ray Diffractograms for the Konawa Soil Showing Patterns for the Coarse and Fine Clay Fractions in the AP, B21t, and C Horizons

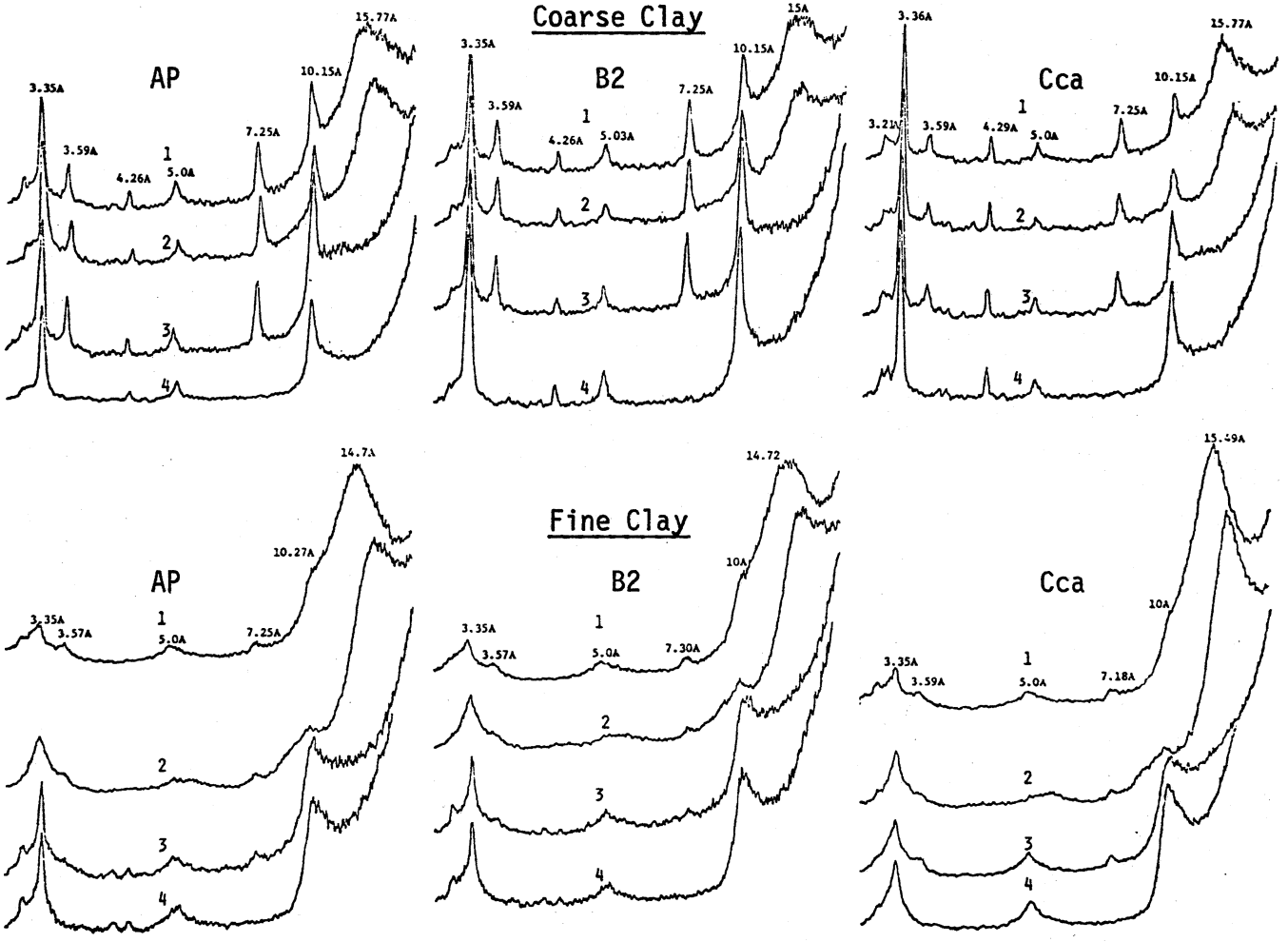


Figure 6. X-ray Diffractograms for the Ulysses Soil Showing Patterns for the Coarse and Fine Clay Fractions in the AP, B2, and Cca Horizons

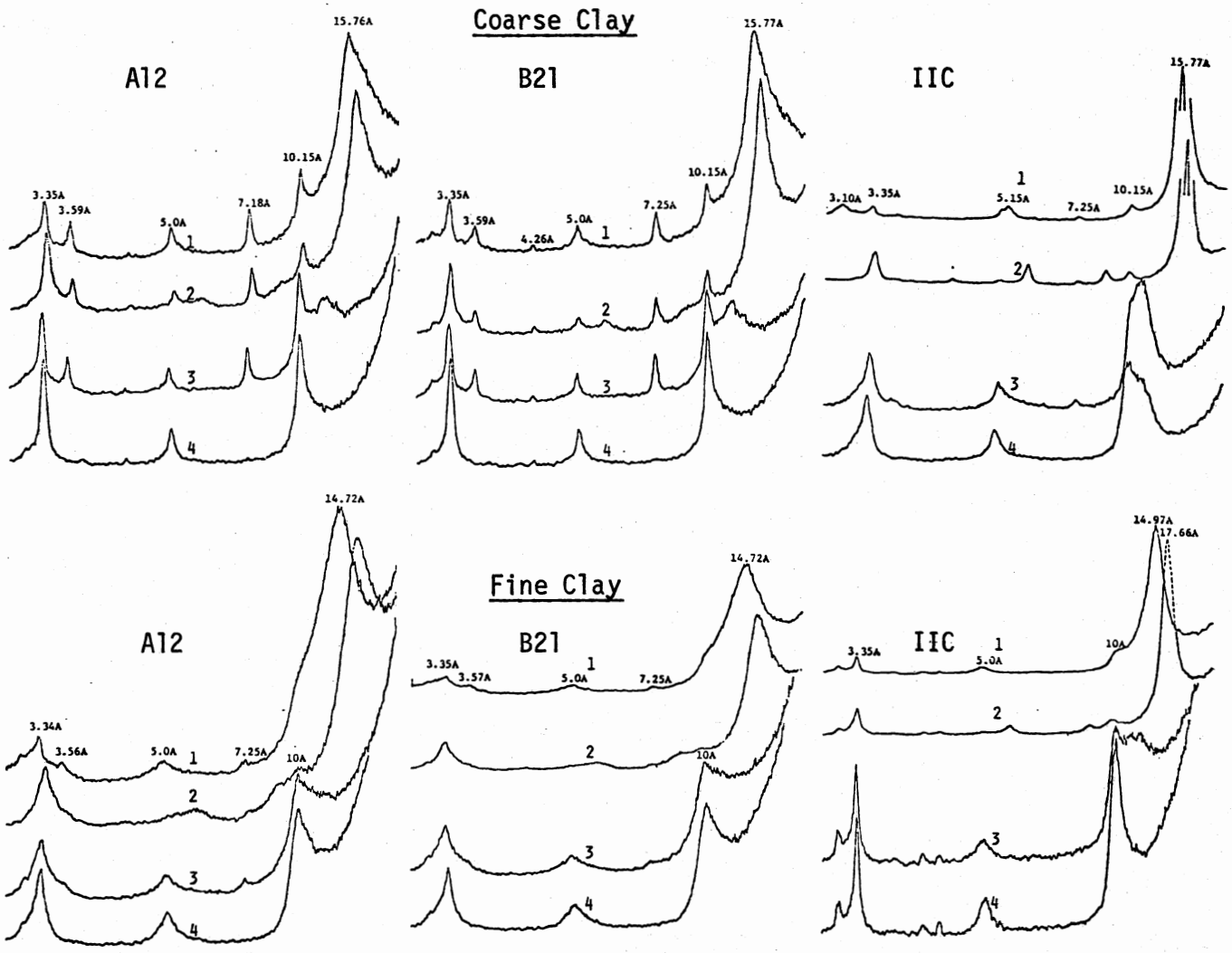


Figure 7. X-ray Diffractograms for the Dill Soil Showing Patterns for the Coarse and Fine Clay Fractions in the A12, B21, and IIC Horizons

solvation. This indicated the presence of large amounts of random interstratified illite and montmorillonite. The coarse clay fraction of the IICr horizon contained relatively larger amounts of vermicullite as shown by the 14.97 Å peak which shifted only to 15.5 Å due to solvation with ethylene glycol. A small peak located at 12-13 Å in the Ca-saturated sample of the coarse clay fraction suggested the presence of random interstratified illite and expansible clay minerals in the A1 and IICr horizons. Presence of regular interstratified illite and 2:1 expansible clays was indicated by a small 25 Å peak in coarse clay fractions of the A1 and B22 horizons. Sharp 7.24 and 3.59 Å peaks which disappeared due to 550°C heating suggested the presence of orderly crystalline kaolinite in the coarse clay fraction. Fine clays, however, did not show sharp basal reflections for kaolinite. Quartz, which was present mainly in coarse clays, was shown by sharp 4.26 and 3.34 Å peaks.

In the Bernow soil (Figure 3), diffuse peaks at 10 and 5 Å were indicative of a highly weathered illite in the coarse clay fractions. Expansible clay minerals were identified by the presence of 14-15 Å peaks in the Ca-saturated samples of coarse clay fractions. The expansible clays, however, partially expanded due to solvation with ethylene glycol and partially collapsed to 10 Å, particularly in the A1 horizon, due to 550°C heating of K-saturated samples. This suggested the partial chloritization of the expansible clay minerals in the coarse clay fractions. The fine clay fractions contained large amounts of montmorillonite as shown by broad, intense peaks of 17-18 Å in ethylene glycol-treated samples. Coarse clays contained relatively larger amounts of orderly crystalline kaolinite and quartz.

In the Aydelotte soil (Figure 4), interlayered 2:1 clay minerals

were suggested by broad, asymmetric 14-15 Å peaks in the Ca-saturated samples of coarse clay fractions in the A1 and B21t horizons. The interlayered clays expanded only partially due to solvation with ethylene glycol and collapsed partially to 10 Å, as shown by asymmetric 10 Å peaks, due to 550°C heating. Fine clays contained large amounts of montmorillonite as shown by broad, intense 17-18 Å peaks obtained from ethylene glycol-treated samples. Discrete illite was shown mainly in coarse clays. Random interstratification of illite and montmorillonite was indicated mainly in the fine clay of the Cr horizon by a broad, intense 12.99 Å peak which shifted to 14.72 Å in the ethylene glycol-solvated sample. Soil chlorite was identified in the coarse and fine clay of the Cr horizon by the presence of a peak at 14 Å in the K-saturated and 550°C heated samples. Lesser amounts of soil chlorite were also identified in the coarse clay fraction of the B21t and A1 horizons. Orderly crystalline kaolinite and quartz were suggested mainly in coarse clays.

In the Konawa soil (Figure 5), interlayered montmorillonite was shown in coarse and fine clays by diffuse peaks at 17-18 Å in the ethylene glycol-treated samples. Montmorillonite was not orderly crystalline in fine clays. Intergrades or chlorite-like clay minerals were indicated, particularly in the coarse clay fraction of the AP horizon,by the presence of small peaks higher than 10 Å in the 550°C heated samples. Discrete illite was identified mainly in coarse clays by peaks at 10 and 5 Å. Orderly crystalline kaolinite and quartz were suggested mainly in the coarse clays.

In the Ulysses soil (Figure 6), montmorillonite was identified in the coarse and fine clays by broad peaks at approximately 15 Å which

shifted to 17-18 A due to solvation with ethylene glycol. The ethylene glycol-treated specimens also showed diffuse, asymmetric peaks higher than 18 Å. This indicated the presence of interlayered and interstratified montmorillonite. Interlayered 2:1 expansible clays were also suggested by asymmetric peaks at 10 Å in 550°C heated samples. Orderly crystalline kaolinite and quartz were identified mainly in the coarse clays.

In the Dill soil (Figure 7), montmorillonite was identified in the coarse and fine clay fractions by the 001 basal reflection at approximately 15 Å. The montmorillonite expanded to 17-18 Å due to solvation with ethylene glycol. Intensity of the sharp 15.77 Å peak in the coarse clay of the IIC horizon was higher than that of the coarse clay fraction in the A12 and B21 horizons. This suggested larger amounts of orderly crystalline montmorillonite in the coarse clay fraction of the IIC horizon. However, the presence of a broad, asymmetric 10 Å peak in the 550°C heated sample indicated that the montmorillonite was partially interlayered. Illite was detected mainly in coarse clays by 10 and 5 Å peaks. Small amounts of kaolinite were indicated in the coarse clay fractions of the A12 and B21 horizons.

Clay Mineralogy of the Parent Materials

The weathered Pennsylvanian shale underlying the Dennis soil contained large amounts of illite in the coarse and fine clay fractions. The amount of illite ranged from 50% in the coarse to 46% in the fine clay. Kaolinite and montmorillonite were the next most dominat clay minerals in the coarse and fine clays, respectively (Table IX). Vermiculite was present in small amounts. Montmorillonite was

TABLE IX

QUANTITATIVE DISTRIBUTION OF CLAY MINERALS IN COARSE AND FINE FRACTIONS OF THE SOILS STUDIED

Horizon	Coarse Clay						Fine Clay					
	Am.‡	Kaol.	Ill.	Ver.	Mont.	Un.	Am.	Kaol.	Ill.	Ver.	Mont.	Un.
	%											
Dennis												
A1	8	15	24	10	9	34	11	14	16	8	44	7
A3	6	14	23	6	5	46	11	11	16	3	46	13
B22t	9	23	20	8	18	22	11	12	18	4	49	6
B31	10	25	27	9	9	20	12	11	24	3	39	11
B32	7	23	32	14	13	11	9	11	31	7	41	1
IICr	2	23	50	12	6	7	7	9	46	8	29	1
Bernow												
A1	8	24	25	6	10	27	12	21	18	5	33	11
A2	8	25	23	4	8	32	11	23	18	5	35	8
B22t	8	33	23	8	17	11	10	22	16	7	33	12
B24t	7	34	27	9	11	12	8	25	20	8	35	4
Aydelotte												
A1	8	16	35	8	29	4	7	15	15	3	58	2
B21t	6	17	33	10	30	4	8	12	12	7	58	3
B23t	6	15	32	11	26	10	7	12	18	9	49	5
B31ca	4	11	39	11	27	8	4	7	26	8	45	10
Cr	3	13	45	6	21	12	3	7	36	3	43	8
Konawa												
AP	6	16	45	6	9	18	9	12	29	2	45	3
A2	7	15	36	5	9	28	14	14	24	1	42	5
B21t	10	22	30	10	24	4	12	12	22	2	48	4
C	12	20	37	8	15	8	17	14	25	2	37	5
Ulysses												
AP	8	13	36	4	27	12	7	7	14	5	62	5
B2	7	12	40	5	20	16	7	7	13	2	69	2
Cca	5	10	46	4	17	18	7	6	12	5	64	6
Dill												
A12	7	13	30	9	36	5	6	8	14	5	65	2
B21	6	12	32	11	35	4	5	7	10	7	68	3
IIC	2	4	21	14	55	3	3	2	22	3	68	2

‡ Am - amorphous, Kaol. - kaolinite, Ill. - illite, Ver. - vermiculite, Mont. - montmorillonite, Un. - unaccounted clay minerals

interstratified primarily with illite in the fine clay, as suggested by a broad, intense 11.62 Å peak in the Ca-saturated sample.

The weathered shale of Permian age, in which Aydelotte is formed was dominated by illite and montmorillonite in the coarse and fine clay fractions, respectively (Table IX). Illite ranged from 45% in the coarse to 36% in the fine clay fraction. Montmorillonite constituted 21 and 43% of the coarse and fine clay, respectively. Illite was mainly interstratified with montmorillonite in the fine clay, as suggested by X-ray diffraction. Kaolinite and vermiculite were present in small amounts, mainly in the coarse clay. X-ray diffraction indicated the presence of small amounts of trioctahedral chlorite in the coarse and fine clay.

The unconsolidated sandstone of Permian age in western Oklahoma was dominated by montmorillonite in the coarse and fine clay fractions. Montmorillonite constituted 55 and 68% of the coarse and fine clays, respectively (Table IX). This may reflect the relative abundance of volcanic products in the sedimentary rocks of this area. Illite was the second most dominant clay mineral. Vermiculite was present in relatively larger amounts (14%) in the coarse clay. Kaolinite was not present in very large amounts in this formation.

Illite and montmorillonite were the major components of clay minerals in the calcareous loess deposits of Tertiary age in the Oklahoma Panhandle. The coarse and fine clay fractions were dominated by illite and montmorillonite, respectively (Table IX). Vermiculite and kaolinite were present in only small amounts. A similar situation occurred in the sandy alluvium deposits of Quaternary age in which the Konawa soil has developed in central Oklahoma. However, kaolinite was present

in larger amounts. It ranged from 20% in the coarse to 14% in the fine clay fraction. Amorphous clay made up a relatively higher portion of the clay.

Distribution of Clay Minerals in the Soils

In Dennis soil, illite was present in larger amounts in the fine and coarse clay fractions of the subsoil (Table IX). Illite was present in smaller amounts in the fine clays. Montmorollinte was the dominant clay in the fine clay fraction. X-ray diffraction analysis suggested vermiculite was not usually present as a discrete mineral in the soils studied, but mainly as a part of mixed layers with montmorillonite and illite. Small amounts of vermiculite in the soils may suggest it is derived mainly from the weathering of illite. The rate of release of K from the interlayer space in illite and transformation to vermiculite by gradual replacement of K by other cations, such as Mg, is considered a diffusion process in opposite directions (Chute and Quirk, 1967). Kittrick (1973) reported that mica-derived vermiculite is a fast-forming, unstable intermediate which disappears from soils by forming other clay minerals depending upon environmental conditions. In the Dennis soil, kaolinite increased with depth in coarse clays. It increased from 15% in the A1 horizon to 25% in the B31 horizon. Bernow and Konawa soils, which are also highly leached and weathered soils, showed increases in kaolinite content as depth increased. Bryant and Dixon (1963) found a similar situation in Ultisols of Alabama and concluded that kaolinite of the coarse clay fraction tends to become depleted in the surface horizons when the soil is highly leached and weathered. The fine clay fractions of these soils contained relatively

lower amounts of kaolinite, which is somewhat uniformly distributed throughout the soil profiles. Amorphous clays constituted only small portions of the clay samples. Fine clay fractions of the highly leached soils contained slightly larger amounts of amorphous clays. Weathered shale and sandstone contained the smallest amounts of amorphous aluminosilicates. SiO_2 to Al_2O_3 molar ratios of the dissolved amorphous clays in the soils were all greater than 3.0. This suggested the amorphous aluminosilicates were highly siliceous or montmorillonitic-like clay minerals.

The large amounts of unaccountable clay minerals, especially in the coarse clay fraction of the upper horizons of Dennis, Bernow, and Konawa soils, could be due mainly to the presence of partially chloritized 2:1 expansible clay minerals in the surface horizons of these highly weathered and leached soils. X-ray diffraction analysis showed larger amounts of interlayer materials in the upper horizons of these soils by the incomplete collapse of the 2:1 expansible clay minerals to 10 Å due to 550°C heating of the K-saturated specimen. The dissolution of interlayer materials by the method of Dixon and Jackson (1959) showed hydroxy-Al, which decreased with depth, was the major compound blocking the interlayer space. The hydroxy-Al interlayers have lowered the CEC and also prevented complete contraction of the 2:1 expansible layer silicates by K in these horizons. Consequently, the CaEC and K/EC of the coarse clay fraction (Table VII) in these horizons were low and similar (low K fixation), resulting in low montmorillonite and vermiculite content by the method of Alexiades and Jackson (1966). Small amounts of interlayers, however, are needed to lower a large portion of CEC. Dixon and Jackson (1962) suggested removal of 1% Al_2O_3 would

increase the CEC by 20 meq/100g if one-third of the charge of Al were satisfied by the clay. Intensity of the 14-15 Å peak in the Ca-saturated specimen of the coarse clay fraction in these horizons indicated that larger amounts of montmorillonite, vermiculite, or both than have been accounted for in Table IX should be present.

The Bernow soil contained relatively larger amounts of kaolinite in both coarse and fine clay fractions than any other soil studied. X-ray diffraction showed that kaolinite in coarse clays was orderly crystalline, while fine clays contained poorly crystalline kaolinite. Kaolinite increased from 24% in the A1 horizon to 34% in the B24t in the coarse clay fractions. The fine clay fraction showed uniform distribution in kaolinite content. X-ray diffraction patterns obtained from the coarse and fine clay fractions suggested the coarse clay in the A1 horizon contained larger amounts of intergrades or chlorite-like clay minerals. The fine clay fraction showed fairly uniform distribution patterns for intergrade clays throughout the soil profile. Illite was distributed uniformly in the coarse and fine clay fractions. Montmorillonite dominated the fine clay fraction and was distributed evenly throughout the soil profile (Table IX).

In the Aydelotte soil, illite was present in smaller amounts in both the coarse and fine clay fractions of the A and B horizons. Illite in the fine clay fraction increased abruptly with depth, ranging from 15% in the A1 horizon to 36% in the Cr horizon. Montmorillonite was present in larger amounts in the A1 and B21t horizons, particularly in the fine clay. This may indicate the displacement of interlayer-K in illite and thus formation of expansible clay minerals in the surface horizons. Generally, the following changes are necessary for

transformation of illite to montmorillonite: (a) depotassication; (b) dealumination of the tetrahedral sheet, and (c) silication of the tetrahedral sheet (Borchardt, 1977). These changes will allow illite to possess a low charge which is required for the formation of montmorillonite. Norrish (1973) suggested that the layer charge reduction was related to oxidation of structural Fe^{++} to Fe^{+++} in the octahedral sheet. Sridhar and Jackson (1974) indicated that the layer charge reduction could be accomplished by the replacement of Al^{+++} and Fe^{+++} in the tetrahedral sheet by Si^{++++}. Raman and Jackson (1966) proposed that proton incorporation into the structure without corresponding electron charge could reduce the layer charge. However, many questions remain to be answered in regard to layer charge reduction during the transformation of illite to 2:1 expansible clay minerals. The presence of stratified sedimentary rocks and loess deposits in central Oklahoma could have influenced the distribution of illite and montmorillonite in this profile. Therefore, further study in regard to distribution of illite and montmorillonite in this soil is needed. Montmorillonite dominated the fine clay fraction of the solum, while both montmorillonite and illite constituted major components of the coarse clay fraction. Small amounts of soil chlorite were identified in both coarse and fine clay fractions, particularly in the Cr horizon, by the presence of 14 $\mathring{A}$ peaks in the K-saturated and 550^{o}C heated specimens. The chlorite appeared to be trioctahedral because the intensity of the 14 $\mathring{A}$ peak increased due to 550^{o}C heating. Also, the removal of interlayer materials showed the amounts of Al and Fe interlayers were quite low in the Cr horizon. The smaller 14 $\mathring{A}$ peak in the surface horizon suggested the chlorite had undergone weathering. Therefore,

large portions of the unaccounted clay minerals in the subsoil were probably chlorite (Table IX). Kaolinite decreased with depth, particularly in the fine clay fractions in which it decreased from 15% in the A1 horizon to 7% in the Cr horizon.

In the Konawa soil, the amounts of illite in the surface horizon were slightly larger than in the subsoil, particularly in the coarse fraction. This situation could be due to the uptake of K (released from plant decay) by montmorillonite or vermiculite during soil formation. Small amounts of montmorillonite in the coarse clay fraction of the surface horizons (as discussed previously) may be the result of chloritization of 2:1 expansible clay minerals which contributed to amounts of unaccountable clays in these horizons. Kaolinite increased in the coarse clay from 16% in the AP to 22% in the B21t horizon. Kaolinite was, however, distributed uniformly in the soil profile in the fine clay fraction.

In the Ulysses and Dill soils, montmorillonite dominated the fine clay fractions, while illite and montmorillonite were the principal components of the coarse clay fractions. Kaolinite was distributed uniformly in both fractions in the solums. In Dill, the abrupt change in amounts of the clay minerals studied from the B21 to the IIC horizon is due to a lithologic discontinuity. The large amounts of montmorillonite in Dill, which has a sandy loam texture throughout the solum, have increased cation exchange capacity and water retention in that soil.

CHAPTER IV

CLAY MINERALOGY OF OKLAHOMA SOILS

Determination of the relative amounts and kinds of clay minerals present in soils is essential. Clay minerals influence (1) physical qualities of soils such as water holding capacity, permeability, shrink-swell potential and plasticity; (2) cation exchange capacity; (3) K and NH_4 fixation potential; (4) K reserve and release rates; and (5) fertility and tillage. Clay minerals also react with natural organic compounds as well as applied herbicides and pesticides. Clay minerals do not all influence the agricultural and engineering uses of soils in the same way.

Montmorillonite is responsible for a large portion of soil cation exchange capacity. The high cation exchange capacity of montmorillonite is available to hold fertilizer cations such as K and NH_4, macronutrients such as Ca and Mg, and micronutrients such as Cu and Zn. Montmorillonite is also responsible for most shrinking and swelling which causes many difficulties in engineering uses of soils. Montmorillonite has a high adhesive property which prevents soil erosion. However, it absorbs large quantities of water, thereby decreasing the strength and stability of the soil, causing destructive landslides and soil creeps. Although montmorillonite increases natural soil fertility, in large amounts it may produce an unfavorable hydraulic condition and restriction of root growth.

Illite has a low cation exchange capacity compared to that of montmorillonite and vermiculite. Through weathering, illite is a potential supply of K for plants. It usually contains small amounts of various minor elements such as Zn and Fe which may be made available to plants by weathering. Micas are known to be nonconductors of heat and electricity; therefore,they are used commercially as insulator materials, particularly muscovite.

Kaolinite has a very low cation exchange capacity; however, it has high reactivity with anions such as phosphate. Soils containing large amounts of kaolinite are naturally acidic and infertile. Therefore they should be limed and fertilized more than other soils.

Vermiculite has much less expansion or shrink-swell properties than montmorillonite. It has, however, high capacity to fix K and NH_4 from fertilizers. The cation exchange capacity is higher than that of montmorillonite.

Clay minerals in soils can originate by different mechanisms: (a) inheritance from soil parent materials; (b) alteration and degradation of soil primary minerals such as biotite and feldspars, and (c) synthesis (Mackenzie, 1965). These mechanisms working under different environmental conditions accompanied with the process of translocation in soils make composition of clay minerals also a function of soil depth. Likewise, weathering with its resulting alteration and synthesis is higher at the soil surface and decreases in intensity with soil depth. However, because of the importance of parent materials in the clay mineral composition of soils, soils in Oklahoma can be grouped into five major areas based on the origin of their parent materials (Figure 8). Clay minerals of 49 soils developed in these major groups are presented

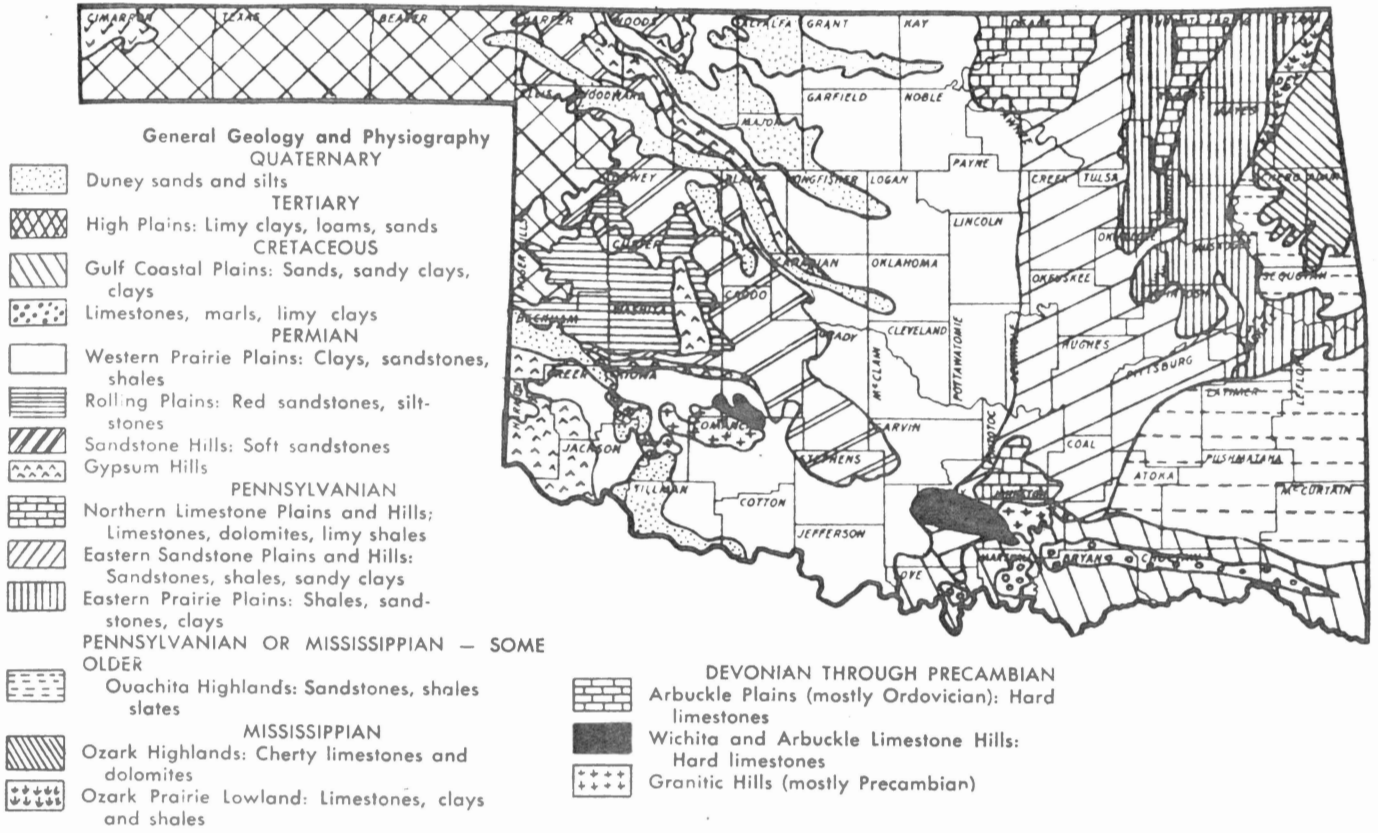


Figure 8. General Geology and Physiographic Areas of Oklahoma (Gray and Galloway, 1959)

in Tables X through XIV. The generalized clay mineral composition of soils from each group and changes which have occurred due, probably, to influences of soil-forming factors have been discussed. A generalized map showing clay mineral distribution has been prepared for Oklahoma (Figure 9). This work is based mainly on the study of clay minerals by the author and other workers (Culver and Gray, 1968; Dawud, 1978; Fanning and Gray, 1959; Gray et al., 1963; Gray and Bakhtar, 1973; Samin, 1971; Stahnke, 1968; Voss, 1974; Wilkinson and Gray, 1954).

Soils Developed in Permian Formations in Central and Western Oklahoma

Nearly all soils in central and western Oklahoma originated from shales, clayey redbeds, siltstone, or sandstones of Permian age.

Study of soil clay minerals in central Oklahoma suggests montmorillonite and illite are the major components. Both montmorillonite and illite are usually the principal components of the coarse clay fraction (2-0.2 micron), while montmorillonite alone dominates the fine clay fraction (less than 0.2 micron). Shales and clay beds usually contain large amounts of illite. However, strongly developed soils such as Kirkland, Bethany, Grainola, and Aydelotte, which have developed in shales and claybeds, contain large amounts of montmorillonite in their solums. Montmorillonite appears to be stable in these soils because of limited leaching and neutral to alkaline pH. Small amounts of chlorite have been identified in sub-horizons of several soils; however, chlorite has ususlly undergone weathering in the soil surface layer. Vermiculite is not usually found as a discrete compound, but as mixed layers with montmorillonite and illite, particularly in the coarse clay

TABLE X

CLAY MINERALOGY OF THE SOILS DEVELOPED IN PERMIAN FORMATIONS IN CENTRAL AND WESTERN OKLAHOMA

Soil	County	Parent Materials	Horizon	X-ray Diffraction‡ Coarse Clay (2-0.2μ)	Fine Clay (<0.2μ)
Zaneis	Payne	stratified sandstone and shale	A1	IKV(Q)	M-V(IK)
			B2t	IKV(Q)	M-V(IK)
			C	IKV-C(Q)	M-V(IK)
Zaneis	Oklahoma	stratified sandstone and shale	A	IKV-C(Q)	M-V(IK)
			B2t	IKV-C(Q)	M-V(IK)
			C	IKV-C(Q)	M-V(IK)
Kingfisher	Kingfisher	shale	A1	IVK(Q)	M-VI(K)
			B2t	IV-CK(Q)	M-VI(K)
			C	IV-CK(Q)	M-VI(K)
Kirkland	Canadian	shale and claybed	AP	IM(Q)	M(IQ)
			B22t	IM(Q)	M(IQ)
Bethany	Canadian	shale and claybed	A11	MI(KQV)	M(IQ)
			B22t	MI(KQV)	M(Q)
Pawhuska-like	Osage	siltstone and sandstone	A1	IV(KQ)	VI(KQ)
			B23t	IV(KQ)	VI(KQ)
			B3	IV(KQ)	VI(KQ)
			C	IM(KQ)	VI(KQ)
Aydelotte	Cleveland	shale and siltstone	A1	IM(KVQ)	M(IKQ)
			B21t	IM(KCVQ)	M(IKCQ)
			Cr	IM(KCQ)	M-I(KCQ)
Grainola	Noble	shale and siltstone	A1	M(IKQ)‡	
			IICr	IM(KQ)	
Waurika	Kay	post-Permian sediment	AP	IK(Q)‡	
			B21t	MI(KQ)‡	
			C2	MI(KQ)	
Waurika	Cotton	reworked Permian shale	A12	IKQ(VMC)	M(IKQC)
			B21	MI(KVCQ)	M(IKQC)
			C3	IKM(VCQ)	M(IKQC)
Windthorst	Pontotoc	hard sandstone and shale	B23t	M-VI(KQ)‡	
Dill	Washita	sandstone	A12	MI(KQ)	M(IK)
			B21	MI(KQ)	M(IK)
			IIC	MI(KQ)	M(I)
Woodward	Harper	soft sandy and silty redbed	A1	I(Q)	MI(Q)
			B2	MI(KQ)	MI(Q)
			B3	IK(Q)	MI(Q)
			C	I(Q)	MI(Q)
Woodward	Washita	stratified sandstone and siltstone	A1	IM-V(KCQ)	M-V(IKC)
			B2	IM-V(KCQ)	M-V(IKC)
			C	IM-V(KCQ)	M-VI(KC)
Quinlan	Washita	stratified sandstone and siltstone	A	IMC(KQ)	MI(K)
			B2	IMC(KQ)	MI(K)
			C	MI(KQ)	M(IK)
Cordell	Washita	siltstone	A1	IM(KQ)	M(I)
			B21	IM(KQ)	M(I)
			R	IM(CKQ)	M(I)
Carey	Custer	siltstone	AP	IVM(KCQ)	MV(ICKQ)
			B22	IV(MKCQ)	MV(ICQ)
			C2	IVC(KQ)	MVC(IQ)
St. Paul	Woodward	silty aeolian and/or alluvial mantle over Permian redbed	A12	IMV(KQ)	M(I)
			B21	IV(MKQ)	M(I)
			C	IV(MKQ)	M(I)
Foard	Cotton	calcareous fine texture redbed	AP	IMV(KCQ)	M
			B22	MVI(KCQ)	M
			C	MV	M
Foard	Comanche	calcerous fine texture redbed	A12	MI(KCVQ)	M(KQ)
			B3Ca	MI(KVQ)	M(KQ)
			C2	MI(KVCQ)	M(KQ)

‡Mineral Code: M - montmorillonite, I - illite, K - kaolinite, V - vermiculite, C - chlorite, Q - quartz M-V - mixed layer M and V. Dominant minerals are enclosed by parentheses. ‡Total clay - less than 2 micron

TABLE XI

CLAY MINERALOGY OF THE SOILS DEVELOPED IN PENNSYLVANIAN FORMATIONS IN EASTERN OKLAHOMA

Soil	County	Parent Materials	Horizon	X-ray Diffraction† Coarse Clay (2-0.2μ)	Fine Clay (<0.2μ)
Parsons	Mayes	shale	A1	IK(MQ)	M(IK)
			B21t	IK(MQ)	M(IK)
			C2	KI(MQ)	M(IK)
Dennis	Rogers	shale	A1	IKM(VQ)	M(IKVQ)
			B21	IKM(VQ	M(IKQ)
			IICr	IKV(Q)	I-M(KVQ)
Dennis	Wagoner	shale	A1	IK(MQ	M(IKQ)
			B2t	IK(MQ)	M(IVK)
			C	IK(MQ)	M(KI)
Enders	Atoka	shale	A2	MIK(Q)‡	
			B22t	MK(IQ)	
			Cr	MK(IQ)	
Enders	Muskogee	shale	A12	m-IK(Q)‡	
			B21t	M-IK(Q)	
			Cr	I(MKQ)	
Niotaze	Osage	shale and sandstone	A2	IM(KQ)	M(VQ)
			B22t	IM(KQ)	M(VQ)
			C	IM-V(Q)	IM(Q)
Tamaha	Haskell	shale	A12	M-VI(K)‡	
Carnasaw	Pushmataha	shale	A1	MIK(Q)‡	
Collins-ville	Haskell	sandstone	B2	M-VIK(Q)‡	

† Mineral Code: M - montmorillonite, I - illite, K - kaolinite, V - vermiculite, C - chlorite, Q - quartz, M-V - mixed layer M and V. Dominant minerals are enclosed by parentheses. ‡ Total clay - less than 2 micron

TABLE XII

CLAY MINERALOGY OF THE SOILS DEVELOPED IN CRETACEOUS FORMATIONS IN SOUTHEASTERN OKLAHOMA

Soil	County	Parent Materials	Horizon	X-ray Diffraction[Ŧ] Coarse Clay (2-0.2μ)	X-ray Diffraction[Ŧ] Fine Clay (<0.2μ)
San Saba	Carter	limestone and limey clay	AP	M(KQ)	M(Q)
			A1	M(KQ)	M(Q)
			AC	M(Q)	M(Q)
Burleson	Marshall	calcareous clayey material	AP	M(IKQ)[‡]	
			AC	M(IKQ)	
			C	M(IKQ)	
Durant	Marshall	calcareous clay bed	A1	M(IKQ)[‡]	
			B21t	M(IKQ)	
			B23t	M(IKQ)	
Ferris	Marshall	calcareous clayey sediment	A1	M(IKQ)[‡]	
			AC2	M(IKQ)	
Gasil	Marshall	loamy material and interbedded sandstone	A2	IMK(Q)[‡]	
			B22t	MI(KQ)	
			Cr	M(IKQ)	
Bernow	Pushmataha	loamy materials and interbedded sandstone	A1	KIM-V(IQ)	MKI(VQ)
			B22t	KIM-V(IQ)	MKI(VQ)

[Ŧ] Mineral Code: M - montmorillonite, I - illite, K - kaolinite, V - vermiculite, C - chlorite, Q - quartz, M-V - mixed layer M and V. Dominant minerals are enclosed by parentheses. [‡] Total clay - less than 2 micron

TABLE XIII

CLAY MINERALOGY OF THE SOILS DEVELOPED IN TERTIARY SEDIMENTS IN THE OKLAHOMA PANHANDLE

Soil	County	Parent Materials	Horizon	X-ray Diffraction‡ Coarse Clay (2-0.2μ)	Fine Clay (<0.2μ)
Ulysses	Texas	calcareous loamy loess	AP	IM(KQ)	M(IK)
			B2	IM(KQ)	M(IK)
			C1	IM(IQ)	M(IK)
Richfield	Texas	calcareous loamy loess	AP	IM(KQ)	M(IK)
			B2t	IM-V(KQ)	M(IK)
			C	IM-V(KQ)	M(IK)

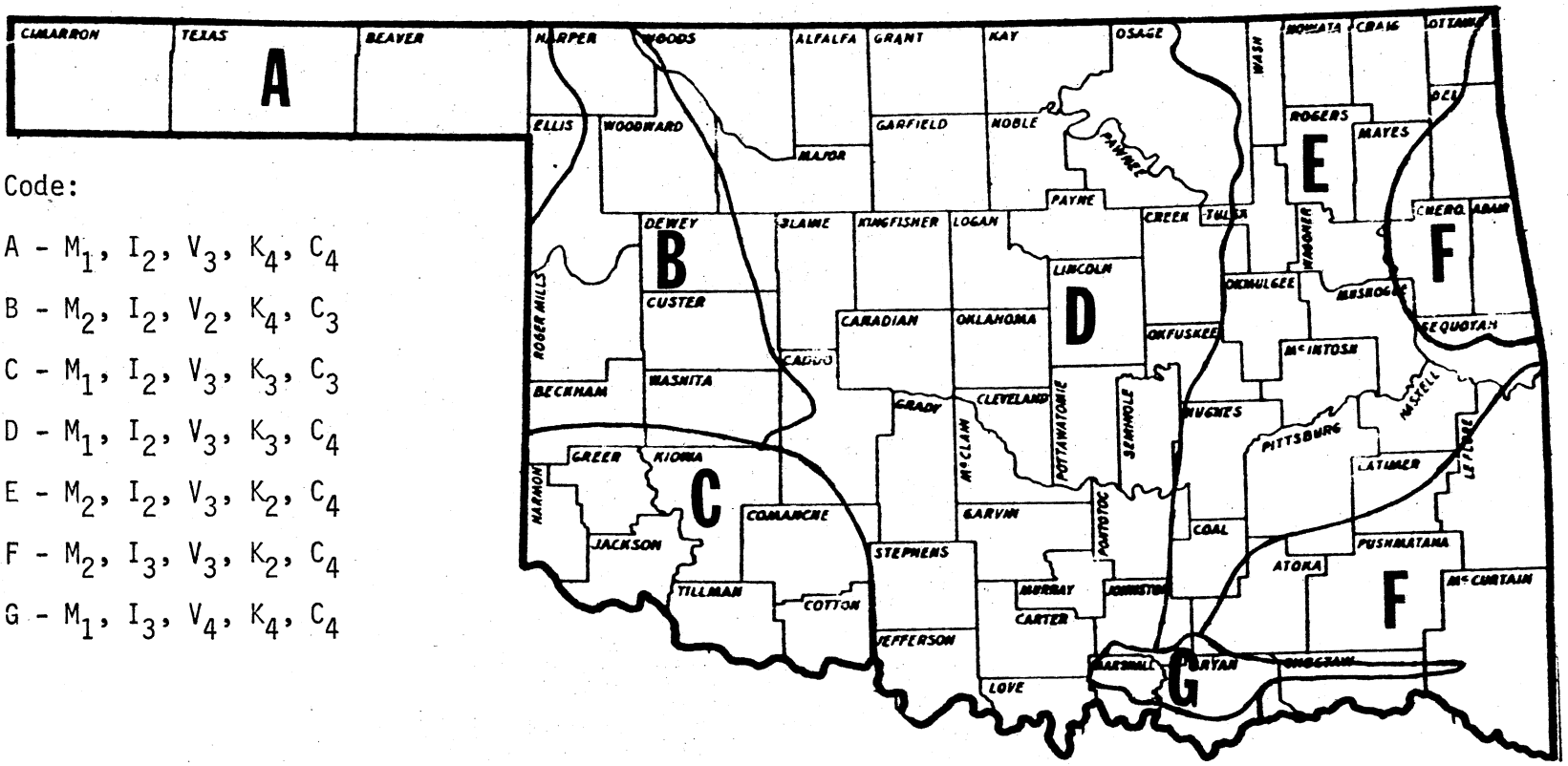
‡Mineral Code: M - montmorillonite, I - illite, K - kaolinite, V - vermiculite, C - chlorite, Q - quartz, M-V - mixed layer M and V. Dominant minerals are enclosed in parentheses.

TABLE XIV

CLAY MINERALOGY OF THE SOILS DEVELOPED IN QUATERNARY SEDIMENTS IN OKLAHOMA

Soil	County	Parent Materials	Horizon	X-ray Diffraction‡ Coarse Clay (2-0.2μ)	X-ray Diffraction‡ Fine Clay (< 0.2μ)
Konawa	Pottawatomie	old alluvium	AP	IKM(VQ)	MI(KQ)
			B22t	IKM(VQ)	MI(KQ)
			C	IKM(VQ)	MI(KQ)
Vanoss	Caddo	old alluvium	AP	MI(KQ)‡	
			B21t	M(IKQ)	
			C1	M(IKQ)	
Granfield	Washita	loamy alluvium or aeolian sediment	AP	IM(KQC)	M(IK)
			B22t	IM(KQC)	M(IK)
			C	IM(KQC)	M(IK)
Nobscot	Woodward	wind reworked sandy alluvial deposit	A1	IVKM(CQ)	MV(IC)
			B21	IVK(MCQ)	MV(IC)
			C	IVK(MCQ)	MV(IC)
Kaufman	Atoka	clayey alluvial deposit	A1	M(IKQ)‡	
			AC2g	M(IKQ)	
Asher	Pottawatomie	recent alluvium	B	M(IKQ)‡	
			C	M(IKQ)	
Kamie	McIntosh	sandy alluvium	B22t	MI(KQ)‡	
Vian	Haskell	reworked sediment	B21t	M-VI(KQ)‡	
Neff	Latimer	loamy alluvium	B22t	MI(KQ)‡	
Norge	Canadian	old alluvium	AP	M-VI(KQ)	M(IQ)
			B22t	M-VI(KQ)	M(IQ)
Bonham	Garvin	old alluvium	A1	IM(KQ)‡	
			B2t	MI(KQ)	
Verdigris	Seminole	alluvium	B2	MI(KQ)‡	

‡ Mineral Code: M - montmorillonite, I - illite, K - kaolinite, V - vermiculite. C - chlorite, Q - quartz M-V - mixed layer M and V. Dominant minerals are enclosed by parentheses. ‡ Total clay - less than 2 micron



Code:

A - M_1, I_2, V_3, K_4, C_4

B - M_2, I_2, V_2, K_4, C_3

C - M_1, I_2, V_3, K_3, C_3

D - M_1, I_2, V_3, K_3, C_4

E - M_2, I_2, V_3, K_2, C_4

F - M_2, I_3, V_3, K_2, C_4

G - M_1, I_3, V_4, K_4, C_4

Figure 9. General Distribution Pattern of Clay Minerals in Oklahoma

M - montmorillonite, I - illite, K - kaolinite, V - vermiculite,
C - chlorite, 1 - >35%, 2 = 20-35%, 3 = 10-20%, 4 - <10%

fraction. Small amounts of kaolinite are usually present in coarse clays. Weathered shales contain mixed layers of illite and montmorillonite which are mostly transformed to montmorillonite in the soil solum. Clay mineralogy of soils in southwestern Oklahoma is similar to that in the central part; however, larger amounts of soil chlorite are often identified. Soils such as Foard contain large amounts of montmorillonite.

Soils developed in siltstone and sandstone of Permian age in western Oklahoma show a similar composition to the soils in the central part. Unconsolidated sandstone underlying Dill and Quinlan soils contains large amounts of montmorillonite. This may reflect the relative abundance of volcanic products found in the sedimentary rocks of this area. Vermiculite and chlorite are usually present in relatively larger amounts in the coarse clay fractions of these soils.

Soils Developed in Pennsylvanian Formations in Eastern Oklahoma

The study of soils developed in shales, claybeds, and sandstones of Pennsylvanian age in eastern Oklahoma indicates that illite, kaolinite and montmorillonite are the main types of clays. Kaolinite and illite are abundant in the coarse clay fractions. Montmorillonite composes large portions of the fine clays. Large amounts of illite are present in the shales in which Enders and Dennis soils developed (Table XI). However, illite has partially weathered to montmorillonite or interstratified illite and montmorillonite in the surface. Kaolinite is usually present in relatively large amounts in Parsons and Dennis soils. The presence of hydroxy-Al interlayers is common in 2:1

expansible clays in the A and B horizons of these soils. In Ultisols and highly leached Alfisols of eastern Oklahoma, illite is usually degraded and has weathered to 2:1 expansible clays which are partially chloritized by hydroxy-Al. Kaolinite is also abundant in these soils. Amorphous clays of the siliceous or montmorillonitic-type alumino-silicates are usually present in larger amounts than in soils developed in central Oklahoma.

Soils Developed in Cretaceous Formations in Southeastern Oklahoma

Soils developed in limestone and calcareous clayey materials of Cretaceous age in southeastern Oklahoma are dominated by montmorillonite. The presence of large amounts of cations such as Ca and Na, low leaching, neutral to alkaline pH, slow permeability, and especially poor drainage favor the formation and stability of montmorillonite in soils such as Burleson, Durant, Ferris, and San Saba of this area. Illite is the next most abundant clay mineral in these soils.

Study of clay minerals of highly leached and weathered soils, such as Bernow, that developed in sandstone and sandy loams of Cretaceous age in southeastern Oklahoma suggests that montmorillonite and kaolinite are the most abundant clay minerals. Kaolinite is the primary clay mineral in the coarse clay fraction, while hydroxy-Al interlayered montmorillonite composes large portions of the fine clay fraction. Illite is usually present in small amounts.

Soils Developed in Tertiary Materials

Study of soils such as Richfield and Ulysses, that developed in

calcareous loamy to clayey material of Tertiary age in the Oklahoma Panhandle, indicates that montmorillonite and illite are the major components of their clay minerals. The coarse clay fraction is composed of large amounts of illite and montmorillonite, while the fine clay is dominated by montmorillonite. Lesser amounts of vermiculite, kaolinite, and soil chlorite are identified in these soils. Vermiculite is present mainly in mixed layers with montmorillonite in the coarse clay fraction.

Soils Developed in Quaternary Deposits

Soils developed in alluvial deposits throughout the state contain a varying mixture of montmorillonite, illite, kaolinite, and vermiculite. Montmorillonite and illite are usually the most abundant clay minerals in these soils. A lesser amount of kaolinite is usually present. In central and western Oklahoma, soils such as Norge, Vanoss, and Granfield contain large amounts of montmorillonite in the clay fractions. Montmorillonite is usually interlayered and poorly crystalline. Illite is the second most dominant clay mineral in these soils. Slowly to very slowly permeable and alkaline soils, such as Kaufman and Asher, which have developed in recent alluvial deposits, are highly montmorillonitic. Illite and kaolinite are present in small amounts in these soils.

CHAPTER V

SUMMARY AND CONCLUSIONS

Six widely occurring Oklahoma soils representing five geologic periods were selected for this study. These soils developed under climatic conditions ranging from a semi-arid climate in the Oklahoma Panhandle with a mean annual precipitation of 48 cm to a humid climate in southeastern Oklahoma with a mean annual precipitation of 119 cm. The soils were Dennis (Pennsylvanian shale), Aydelotte (Permian shale and siltstone), Bernow (Cretaceous sandstone), Konawa (Quaternary sandy alluvium), Dill (Permian sandstone), and Ulysses (Tertiary loess deposit). These soils also represented four major soil orders in Oklahoma: Alfisols, Mollisols, Inceptisols, and Ultisols.

Selected chemical properties and particle size distribution were determined on the six soils. Soil carbonates, organic matter, and free iron oxides were removed. The coarse (2-0.2 micron) and fine clay fractions (less than 0.2 micron) were separated. Amorphous alkali-soluble aluminosilicates and hydroxy-Al and -Fe interlayers were removed and measured. X-ray diffraction patterns were obtained on Ca-saturated, ethylene glycol-solvated, K-saturated, and 550^{o}C heated K-saturated samples. Quantitative distributions of kaolinite plus halloysite, illite, vermiculite, and montmorillonite were determined for each soil.

Hydroxy-Al was indicated as the major compound blocking the interlayer space in all soils. Largest amounts of Al were found in the A

horizon and top portions of the B horizon. X-ray diffraction analysis also indicated that 2:1 expansible clays were partially interlayered, particularly in the coarse clay fraction. Fine clays showed somewhat uniform distribution patterns for interlayer materials in the soil profile. The presence of interlayers was clearly suggested in the coarse clay fractions of the surface horizons of Dennis, Bernow, and Konawa soils, which are highly leached and weathered, by large amounts of unaccounted clay minerals. Al-interlayers have blocked the interlayer space and lowered the CEC of the clays. Consequently, 2:1 expansible clay minerals were underestimated in the coarse clay fraction of these soils. Hydroxy-Fe interlayers were quite low in the soils studied.

Quantitative determination of clay minerals suggested that illite was the major component of the coarse and fine clay fractions of the Pennsylvanian shale. Kaolinite and montmorillonite were the other important clay minerals. The same situation occurred in the Permian shale, but montmoillonite was present in larger amounts with lesser amounts of kaolinite. Weathered sandstone of Permian age in western Oklahoma was dominated by montmorillonite. Illite and montmorillonite were the major components of the studied Tertiary loess and Quaternary sandy alluvium.

In the Dennis soil, kaolinite and illite were the main components of the coarse clay, while montmorillonite composed a large portion of the fine clay fraction. Kaolinite increased with depth in Dennis, Bernow, and Konawa soils, due to depletion in surface horizons of these highly weathered and leached soils. Illite increased with depth in Dennis and Aydelotte soils, reflecting a high degree of weathering and

displacement of K-interlayers at the soil surface. Vermiculite was present in only small amounts, mainly in mixed layers with illite and montmorillonite. Illite and kaolinite constituted large portions of the coarse clay fraction of Bernow and Konawa soils. The presence of chloritized 2:1 expansible clay minerals was suggested, particularly in the coarse clay fraction of these soils, by X-ray diffraction analysis. Montmorillonite, illite, and kaolinite were the main components of the fine clay fraction. In Aydelotte, Ulysses, and Dill soils, illite and montmorillonite made up large portions of the coarse clay fraction, while montmorillonite dominated the fine clay fraction. In Aydelotte, kaolinite increased in the surface horizons, especially in the fine clay. Amorphous aluminosilicates made up only small portions of the clays studied.

Illite, montmorillonite, and kaolinite were generally the main components of the coarse clay fraction in Oklahoma soils. Montmorillonite was usually the dominant mineral in the fine clay fraction. Vermiculite was present in small amounts, mainly in the coarse clay. Chlorite was present in small amounts; however, montmorillonite or vermiculite with hydroxy-Al interlayers were usually found in the soils, especially in the coarse clay fractions of the A horizon and upper portions of the B horizon.

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APPENDIX

SOIL DESCRIPTIONS

Soil Type: Aydelotte silt loam

Soil Number: 76-OK-14-24-1/9

Location: Cleveland County, 1700 feet north and 1250 feet east from the southwest corner of Sec. 2, T10N, R2W

Physiography: Upland side slope

Relief: Convex

Slope: 3%

Parent Material: Alternative layers of red shale and siltstone of Permian Age

Drainage: Well drained

Permeability: Very slow

Vegetation: Native tall and midgrasses

Soil Profile:

Horizon	Depth (cm)	Description (Colors are for moist soil)
A1	0-13	Very dark grayish-brown (10YR3/2) silt loam; moderate fine subangular blocky breaking to granular structure; friable; common coarse roots; clear smooth boundary.
B1	13-23	Dark brown (7.5YR3/2) silty clay loam; moderate fine subangular blocky breaking to strong medium granular structure; clay films on the faces of peds; common fine roots; firm; clear smooth boundary.
B21t	23-53	Reddish brown (5YR4/3) silty clay; moderate medium prismatic breaking to moderate medium and coarse blocky structure; ped faces dark reddish-brown (5YR3/4); clay films on the ped faces; very firm; common roots; gradual smooth boundary.
B22t	53-69	Reddish-brown (5YR4/4) silty clay; weak coarse prismatic breaking to moderate coarse subangular blocky structure; ped faces dark reddish-brown (5YR3/4); common fine Fe and Mn bodies; clay films on ped faces; faces of prisms covered with dark material from above horizon; few nonintersecting slickensides; very firm; few fine roots; gradual wavy boundary.

Horizon	Depth (cm)	Description
B23t	69-104	Red (2.5YR/6) silty clay; weak coarse subangular blocky; ped faces dark red (2.5YR 3/6); common fine and medium Fe and Mn bodies; few nonintersecting slickensides; clay films on ped faces; few large masses of calcium carbonate bodies at 77 cm depth; very firm; gradual wavy boundary.
B24t	104-137	Red (2.5YR4/6) silty clay; weak coarse subangular blocky breaking to fine sizes; ped faces dark red (2.5YR3/6); common Fe and Mn bodies; few bodies of calcium sulfate; very firm; gradual wavy boundary.
B31ca	137-175	Red (2.5YR4/6) heavy silty clay loam; weak coarse subangular blocky breaking to fine sizes; ped faces dark red (2.5YR3/6); clay films on faces of peds; black bodies of Fe and Mn; few fine roots; few bodies of calcium carbonate; firm; gradual wavy boundary.
B32ca	175-185	Red (2.5YR4/6) silty clay loam; weak coarse subangular blocky breaking to fine sizes; common bodies of shale and siltstone; common coarse bodies of calcium carbonate; firm, friable; clear wavy boundary.
Cr	185-239	Alternating layers of red (2.5YR4/6) shale and siltstone.

Soil Type: Bernow fine sandy loam

Soil Number: 75-OK-64-4-1/6

Location: Pushmataha County, 920 feet north and 420 feet west of the southeast corner of Sec. 16, T4S, R16E

Physiography: Upland

Relief: Convex

Slope: 2%

Parent Material: Weakly cemented sandstone of the Paluxy Unit of Cretaceous Age

Drainage: Well drained

Permeability: Moderate

Vegetation: Trees with an understory of grasses

Soil Profile:

Horizon	Depth (cm)	Description (Colors are for moist soil)
A1	0-13	Brown (10YR5/3) fine sandy loam; weak fine granular structure; slightly hard, very friable; many fine roots; medium acid; clear smooth boundary.
A2	13-25	Light yellowish brown (10YR6/4) fine sandy loam; weak fine granular structure; slightly hard, very friable; many fine roots; medium acid; abrupt smooth boundary.
B21t	25-51	Brownish yellow (10YR6/6) sandy clay loam; weak medium prismatic structure; hard, friable; common fine roots; nearly continuous clay films on faces of peds; strongly acid; gradual smooth boundary.
B22t	51-97	Brownish yellow (10YR6/6) sandy clay loam; moderate medium prismatic structure; hard, friable; common fine roots; nearly continuous clay films on faces of peds; very strongly acid; gradual smooth boundary.
B23t and A'22	97-142	Yellowish red (5YR5/8) sandy clay loam (B part); moderate coarse prismatic structure; very hard, firm; about 10% is light gray (10YR 7/2) fine sandy loam (A part) vertical ped coatings; massive; hard, friable; nearly

Horizon	Depth (cm)	Description
		continuous clay films on faces of peds; very strongly acid; diffuse smooth boundary.
B24t and A'22	142-203	Yellowish red (5YR5/8) sandy clay loam (B part); weak coarse prismatic structure; very hard, firm; about 10% is light gray (10YR7/2) fine sandy loam (A part) vertical ped coatings; massive; hard, friable; patchy clay films on faces of peds; very strongly acid.

Soil Type: Dennis silt loam

Soil Number: 76-OK-66-1-1/8

Location: Rogers County, about 1/2 mile north of Claremore; 650 feet north and 490 feet east of the center of Sec. 4, T21N, R16E

Physiography: Upland

Relief: Convex slope

Slope: <1%

Parent Material: Reworked shales of Pennsylvanian Age

Drainage: Moderately well drained

Permeability: Slow

Vegetation : Tall grass prairie

Soil Profile:

Horizon	Depth (cm)	Description (Colors are for moist soils)
A1	0-28	Very dark grayish-brown (10YR3/2) silt loam; moderate coarse subangular blocky breaking to granular structures; lots of roots and worm acritivites; clear smooth boundary.
A3	28-28	Dark grayish-brown (10YR4/2) silt loam; few fine faint dark brown (10YR4/3) and distinct brown (7.5YR5/4) mottles; moderate fine subangular blocky breaking to medium granular structure; few fine hard siltstone; fine and medium roots. Few earthworm activities; clear wavy boundary.
B21t	38-53	Brown (10YR4/3) silty clay; few fine prominent yellowish-red (5YR4/6) and fine faint dark grayish-brown (10YR4/2) mottles; moderate coarse subangular and angular blocky breaking to fine sizes; few fine and medium roots; ped face slightly darker; clay films on faces of peds; some worm activity; clear, wavy boundary.
B22t	53-84	Yellowish-brown (10YR5/4) with lesser amount (10YR5/6) silty clay; common coarse distinct streaks and gray (10YR5/1) mottles; few fine prominent yellowish-red (5YR4/6) mottles; moderate coarse blocky breaking to fine sizes; few very fine siltstone; ped faces slightly darker; clay films on faces of peds; common

Horizon	Depth (cm)	Description
		slickensides; few to common fine roots; gradual wavy boundary.
B23t	84-102	Yellowish-brown (10YR5/6, 10YR5/4) silty clay; many coarse distinct gray (10YR6/1) mottles; moderate medium breaking to fine blocky structure; common stains of iron and manganese oxides; clay films on faces of peds; iron and manganese coatings; few fine roots; gradual wavy boundary.
B31	102-147	Matrix is yellowish-brown mottles and streaks (10YR5/4, 10YR5/6) silty clay with gray (10YR5/1, 10YR7/1) heavy silty clay loam; moderate medium breaking to fine blocky structure; black (10YR2/1) coatings of iron and manganese oxides; less than 2 percent bodies of iron and manganese oxides; few fine roots; clear wavy boundary.
B32	147-206	Yellowish-brown (10YR5/6) silty clay loam; common coarse gray (10YR5/1, 6/1) yellowish brown 10YR5/4), and black (10YR2/1) mottles and streaks; moderate medium subangular blocky and blocky structure; no noticeable roots; black coatings; few shale and sandstone fragments; few rounded sandstone gravels; clear smooth boundary.
IICr	206-221	Bedded shales with pockets of weathered material.

Soil Type: Dill very fine sandy loam

Soil Number: 75-OK-75-4-1/5

Location: Washita County, about 600 feet northeast of Turkey Creek; 400 feet west and 600 feet south of the northeast corner of Sec. 21, T11N, R19W

Physiography: Upland

Relief: Convex slope

Slope: 2%

Parent Material: Weakly cemented noncalcareous sandstone of the Elk City formation of Permian age

Drainage: Well drained

Permeability: Moderately rapid

Vegetation: Mid- to tall grasses

Soil Profile:

Horizon	Depth (cm)	Description (Colors are for moist soils)
A1	0-10	Reddish brown (5YR4/3) fine sandy loam; dark reddish brown (5YR4/4) moist; weak fine granular structure; hard,very friable; many fine roots; few fine pores; neutral; clear smooth boundary.
A12	10-36	Reddish brown (5YR4/4) fine sandy loam; dark reddish brown (5YR3/4) moist; weak fine medium granular structure; hard,very friable; many fine roots; common worm casts; neutral; gradual smooth boundary.
B21	36-53	Reddish brown (2.5YR4/4) heavy fine sandy loam; dark reddish brown (2.5YR3/4) moist; weak medium prismatic structure parting to weak fine granular structure; hard,very friable; many roots; common worm casts; few krotovinas; neutral; gradual smooth boundary.
B22	53-84	Reddish brown (2.5YR4/4) heavy fine sandy loam; dark reddish brown (2.5YR3/4) moist; weak medium prismatic structure parting to weak fine granular structure; hard,friable; many roots; common worm casts; few krotovinas; few fragments of soft sandstone; neutral; diffuse wavy boundary.

Horizon	Depth (cm)	Description
IIC	84-119	Red (10YR5/6) soft sandstone; red (10YR4/6) moist, with thin bands of dark red (2.5YR3/6) soft sandstone; bands calcareous.

Soil Type: Konawa loamy fine sand

Soil Number: 75-OK-63-1-1/5

Location: Pottawatomie County, 700 feet south and 100 feet west of the northeast corner of Sec. 36, T6N, R4E

Physiography: Stream terrace

Relief: Convex slope

Slope and Land Form: 3% convex southeast facing uplands

Parent Material: Sandy and loamy sediments of Quaternary age

Drainage: well drained

Permeability: Moderate

Vegetation: Tame pasture of bermuda grass and native grasses

Soil Profile:

Horizon	Depth (cm)	Description (Colors are for dry soil unless otherwise stated)
AP	0-15	Grayish brown (10YR5/2) loamy fine sand; dark grayish brown (10YR4/2) moist; weak fine granular structure; soft,very friable; slightly acid; clear smooth boundary.
A2	15-36	Very pale brown (10YR7/3) loamy fine sand,brown (10YR5/4) moist;single grained; soft,very friable;medium acid; clear smooth boundary.
B21t	36-66	Yellowish red (5YR5/6) sandy loam; yellowish red (5YR4/6) moist; moderate coarse prismatic structure parting to weak medium subangular blocky structure; very hard,friable; clay films on ped faces and bridging sand grains; medium acid; diffuse smooth boundary.
B22t	66-97	Yellowish red (5YR5/6) sandy loam; yellowish red (5YR4/6) moist; weak coarse prismatic structure parting to moderate medium subangular blocky structure; hard,friable; patchy clay films on ped faces and bridging sand grains; medium acid; diffuse smooth boundary.
B3	97-137	Yellowish red (5YR5/6) fine sandy loam; yellowish red (5YR4/6) moist; weak coarse prismatic structure; hard,friable; medium acid; diffuse smooth boundary.

Horizon	Depth (cm)	Description
C	137-178	Yelowish red (5YR5/8) loamy fine sand; yellowish red (5YR4/8) moist; massive; hard, friable; medium acid; few slightly brittle peds. The C horizon was visible in the back hoe pit to a depth of 8 feet. A hand auger was used in the bottom of the pit to observe between the 8 and 14 foot depths; the C horizon loamy fine sand was present throughout the 8 foot to 14 foot depths.

Soil Type: Ulysses clay loam

Soil Number: 76-OK-70-1-1/5

Location: Texas County, 720 feet north and 430 feet east of the southwest corner of Sec. 36, T2N, 413E. This profile represents the Ulysses soil that ranges toward the Richfield series

Physiography: Upland

Relief: Weak convex

Slope: 0.5%

Parent Material: Calcareous wind laid silt (loess) of Tertiary age

Drainage: Well drained

Permeability: Moderate

Vegetation: Short grasses

Soil Profile:

Horizon	Depth (cm)	Description (Colors are for moist soil)
AP	0-15	Very dark grayish brown (10YR3/2) clay loam; weak fine and medium granular; friable, slightly hard; gradual smooth boundary.
B1	15-38	Very dark grayish brown (10YR3/2) clay loam; weak to moderate medium subangular blocky; friable to firm,hard; gradual smooth boundary.
B2	38-91	Dark brown (10YR3/3) clay loam; weak medium subangular blocky; friable to firm,hard; gradual smooth boundary.
B3ca	91-122	Brown (10YR3/3) clay loam; weak coarse granular; friable,slightly hard; soft concretion of $CaCO_3$; strongly calcareous; gradual smooth boundary.
Cca	122-163	Brown (10YR4/3) loam; porous massive; friable, slightly hard; strong calcareous.

VITA

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